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FLIGHT TEST HANDLING QUALITIES OF THE X-24A LIFTING BODY

AFFTC

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TECHNOLOGY DOCUMENT No. 71-11

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FLIGHT TEST HANDLING QUALITIES OF THE X-24A LIFTING BODY

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FOREWORD

This technology document presents an analysis of the handling qualities of the X-24A lifting body research vehicle. The X-24A made 28 flights at Edwards Air Force Base between 17 April 1969 and 4 June 1971 and was flown by one NASA and two Air Force research test pilots. The test program was conducted jointly with the NASA Flight Research Center (FRC). References 1 through 8 are related documents which have been or will be published.

The author wishes to acknowledge the efforts of Mr. Christopher Nagy who performed the root locus analyses, Mr. David Richardson who assembled the longitudinal trim data, Mr. Paul Kirsten who was responsible for the simulator studies, and Mr. John Manke, Major Jerauld Gentry, and Major Cecil Powell who provided pilot comments.

The participation of AFFTC personnel in this program was authorized by AFFTC Project Directive 69-38. The assigned Program Structure was 680A.

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ABSTRACT

The handling qualities of the X-24A were determined through a combination of qualitative pilot comments, numerical pilot ratings, and direct and indirect analyses of recorded flight test data. A fixed base six-degree-of-freedom simulator was used extensively to evaluate predicted handling characteristics and to establish trends which were confirmed in flight. The handling characteristics of the X-24A during an approach and landing in still air were excellent. The lateral control capability was inadequate in crosswinds above 10 knots, and the vehicle had a high susceptibility to lateral upsets in light turbulence which was initially disturbing to the pilot. The longitudinal trim change associated with landing gear extension was also considered undesirable. The transonic handling qualities were adequate for a research mission, but precise control was extremely difficult due to an inherent lateral pilot-induced-oscillation tendency and continual small disturbances in the longitudinal and lateral axes. At supersonic speeds the handling qualities were excellent; however, supersonic evaluation time was quite short. The rocket engine exhaust plume influenced the handling qualities by producing a longitudinal trim change at transonic conditions and a reduction in directional stability at supersonic conditions. A limited amount of quantitative handling qualities data from X-24A tests were compared with criteria from a proposed specification for lifting reentry vehicles. In most cases the X-24A met the proposed specification. Several of the test maneuvers in the specification were impractical for a vehicle of this type. Some handling qualities deficiencies which were uncovered during the test program were not identifiable by application of the proposed specification.

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list of abbreviations and symbols

Item	Definition	Units
a_Y	acceleration along body y axis (lateral)	ft/sec^2
b	reference span (10 ft)	ft
$\bar{c}$	reference length (23 ft)	ft
cg	center of gravity (reference 57% $\bar{c}$)	percent $\bar{c}$
C_ℓ	rolling moment coefficient	dimensionless
C_{ℓ_P}	$\partial C_\ell / \partial (Pb/2V_t)$	per rad
C_{ℓ_R}	$\partial C_\ell / \partial (Rb/2V_t)$	per rad
$C_{\ell_{\delta a}}$	$\partial C_\ell / \partial \delta a$	per rad
$C_{\ell_{\delta r}}$	$\partial C_\ell / \partial \delta r$	per rad
C_{ℓ_β}	$\partial C_\ell / \partial \beta$	per rad or per deg
C_m	pitching moment coefficient	dimensionless
C_{m_α}	$\partial C_m / \partial \alpha$	per rad
C_n	yawing moment coefficient	dimensionless
C_{n_P}	$\partial C_n / \partial (Pb/2V_t)$	per rad
C_{n_R}	$\partial C_n / \partial (Rb/2V_t)$	per rad
C_{n_β}	$\partial C_n / \partial \beta$	per rad or per deg
$C^*_{n_\beta}$, $C_{n_\beta \, dyn}$	$C_{n_\beta} \cos \alpha - \frac{I_z}{I_x} C_{\ell_\beta} \sin \alpha$	per rad
$C_{n_{\delta a}}$	$\partial C_n / \partial \delta a$	per rad
$C_{n_{\delta r}}$	$\partial C_n / \partial \delta r$	per rad
C_Y	side force coefficient	dimensionless
C_{Y_β}	$\partial C_Y / \partial \beta$	per rad
$C_{Y_{\delta a}}$	$\partial C_Y / \partial \delta a$	per rad
$C_{Y_{\delta r}}$	$\partial C_Y / \partial \delta r$	per rad

Item	Definition	Units
g	acceleration due to gravity	32.2 ft per sec^2
I_x	moment of inertia about the x-body axis	slug-ft^2
I_y	moment of inertia about the y-body axis	slug-ft^2
I_{xz}	cross product of inertia	slug-ft^2
I_z	moment of inertia about the z-body axis	slug-ft^2
$j\omega_d$	imaginary root of characteristic equation	rad/sec
K_{a_y}	lateral acceleration feedback gain in degrees of δr surface per ft/sec^2 of a_y	deg/ft/sec^2
KRA	aileron-to-rudder interconnect	percent or deg/deg
K_p	roll SAS gain in degrees of δa surface per degree per second of roll rate	deg/deg/sec
K_{pilot}	pilot roll feedback gain in degrees of commanded δa surface per degree per second of roll rate	deg/deg/sec
K_q	pitch SAS gain in degrees of δe surface per degree per second of pitch rate	deg/deg/sec
K_r	yaw SAS gain in degrees of δr surface per degree per second of yaw rate	deg/deg/sec
L/D	lift to drag ratio	dimensionless
M_n	Mach number	dimensionless
n_z	normal load factor	g's
P	body axis roll rate	deg/sec or rad/sec
PIO	pilot-induced oscillation	- - -
P_{osc}/P_{ave}	ratio of the oscillatory component of roll rate to the average component of roll rate (reference 9)	dimensionless
$\delta a/P$	pilot transfer function in lateral axis - commanded surface deflection per degree per second roll rate ($\delta a = K_{pilot} \cdot P$, $\delta r = KRA \cdot \delta a_s$)	deg/deg/sec
$\bar{q}$	dynamic pressure	lb per ft^2
R	body axis yaw rate	deg/sec or rad/sec

Item	Definition	Units
S	reference area (162 ft^2)	ft^2
SAS	stability augmentation system	- - -
V_t	true airspeed	ft per sec
α or α_t	true angle of attack (corrected for upwash)	degrees
β	angle of sideslip	degrees
Δ	prefix meaning increment	- - -
δa_L	total aileron deflection, lower flaps	degrees
δa_S	lateral stick position	inches
δe_L	elevator deflection, lower flaps	degrees
δe_S	longitudinal stick position	inches
δe_U	elevator deflection, upper flaps	degrees
δ_{LL}	lower left flap position	degrees
δ_{LR}	lower right flap position	degrees
δR_B	rudder bias position	degrees
δr	average rudder deflection	deg or rad
δU_B	upper flap bias position	degrees
ϕ	bank angle	degrees
ϕ_t	time to reach 45-degree bank angle	sec
θ	pitch attitude	degrees
ψ_β	phase angle in a cosine representation of the Dutch roll component of sideslip (reference 9)	degrees
ζ	damping ratio	dimensionless
$\zeta\omega_n$	real root of characteristic equation	rad/sec
ω_d	Dutch roll damped natural frequency	rad/sec
ω_n	Dutch roll undamped natural frequency	rad/sec
$\omega_{n_{sp}}$	longitudinal short period undamped natural frequency	rad/sec

Note: The body axis system is used throughout this report.

INTRODUCTION

VEHICLE DESCRIPTION

The X-24A was a piloted, wingless, rocket-powered lifting body research vehicle. It was air launched from a modified NB-52 aircraft, rocket boosted to transonic and supersonic test conditions, and then flown unpowered to an approach and landing on Rogers Dry Lake at Edwards AFB. The general arrangement and overall dimensions of the X-24A are illustrated in figure 1.

The general configuration consisted of a contoured body with one center fin and two outboard vertical fins at the aft end. Control surfaces consisted of two upper and two lower flaps located at the aft end of the body, and two upper and two lower rudders on the outboard tip fins (figure 2). Control inputs in pitch and roll were transmitted mechanically to the lower flap actuators. When either lower flap was fully retracted (0-degree position), pitch and roll inputs were transferred through a clapper mechanism to the corresponding upper flap.

The upper and lower flaps could also be biased either open or closed within a range of positions. The two pairs of rudder surfaces could be deflected symmetrically as a bias feature. These control surfaces were flared outward at transonic and supersonic speeds. The flaps were closed and the rudders biased inward during the configuration change at approximately 0.6 Mach number prior to the high energy approach and landing. Directional control was provided by deflection of the upper rudder surfaces in unison. In addition to the normal deflection of the rudders with rudder pedal movement, an aileron-to-rudder interconnect system allowed pilot lateral stick inputs to deflect the upper rudders in proportion to the commanded aileron deflection. The ratio of rudder deflection per degree of aileron deflection (KRA) was adjustable from zero to 0.25 deg per deg (displayed as 0 to 50 percent on the cockpit indicator). This ratio could be either selected manually or programmed automatically as a function of angle of attack and Mach number.

The electronic portion of the control system consisted of a triply-redundant (fail-operational, fail-safe) stability augmentation system (SAS) which incorporated rate feedback in the pitch, roll, and yaw axes. Control of the rate-feedback gains was through three seven-position rotary switches in the cockpit. The SAS mode switches also allowed selection of zero gain for the purpose of performing test maneuvers without SAS inputs. A more complete description of the vehicle and instrumentation is given in reference 2. A detailed description of the flight control system may be found in reference 4.

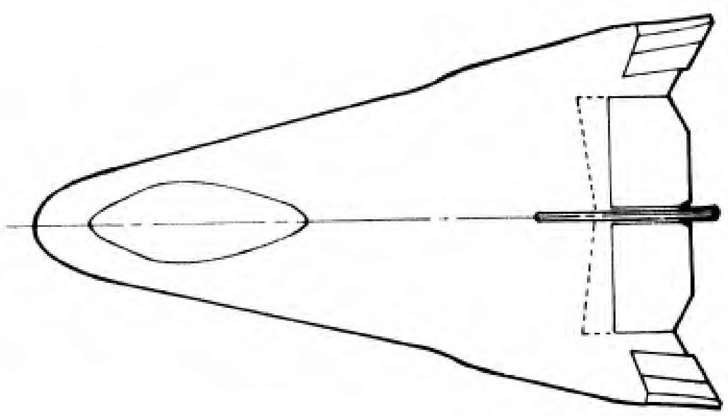
GENERAL HANDLING CHARACTERISTICS

The geometry of a wingless lifting body produces several unusual stability and control characteristics which are a challenge to the aerodyamicist and the control system designer. The X-24A configuration was typical of the class of medium hypersonic lift-to-drag ratio (L/D) vehicles (L/D = 1.3 at Mach 20). The short, stubby fuselage produced low direcional stability and a rather short coupled vehicle in the pitch axis. The highly swept planform with tip fins resulted in quite high dihedral effect, while the lack of protruding surfaces (wings) resulted in a low

rolling moment of inertia and low aerodynamic roll damping. This combination produced very high roll-to-sideslip ratios (ϕ/β = 4 to 8 for the basic vehicle with SAS off). Lateral control surfaces were necessarily quite close to the rolling axis and thus relatively ineffective. The flow field produced over the upper rear portion of the vehicle resulted in very large interaction effects between the vertical and horizontal control surfaces. An aileron-to-rudder interconnect was used in the X-24A control system to minimize the roll control coupling effects and to enhance the roll power. The flap and rudder bias feature allowed the control surfaces to be flared outward at transonic speed to increase the "shuttlecock" stability at the expense of higher drag. The X-24A control system was necessarily complex, but possessed a great deal of built-in flexibility including both manual and automatic modes for most of the control system features.

Reference Dimensions

Length, $\bar{c}$	= 23 ft
Span, b	= 10 ft
Area, S	= 162 ft^2
cg	= 57 % $\bar{c}$



Typical Mass Properties

	Launch	Landing
Weight	11,450	6,300 lb
cg	56	57 %
I_x	1,900	1,450 slug-ft^2
I_y	8,300	8,300 slug-ft^2
I_z	9,400	9,000 slug-ft^2
I_{xz}	-50	0 slug-ft^2

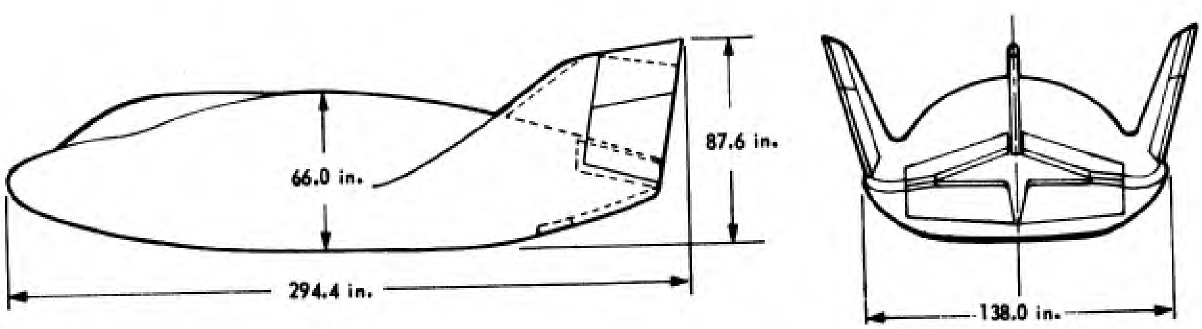


Figure 1 X-24A Three View

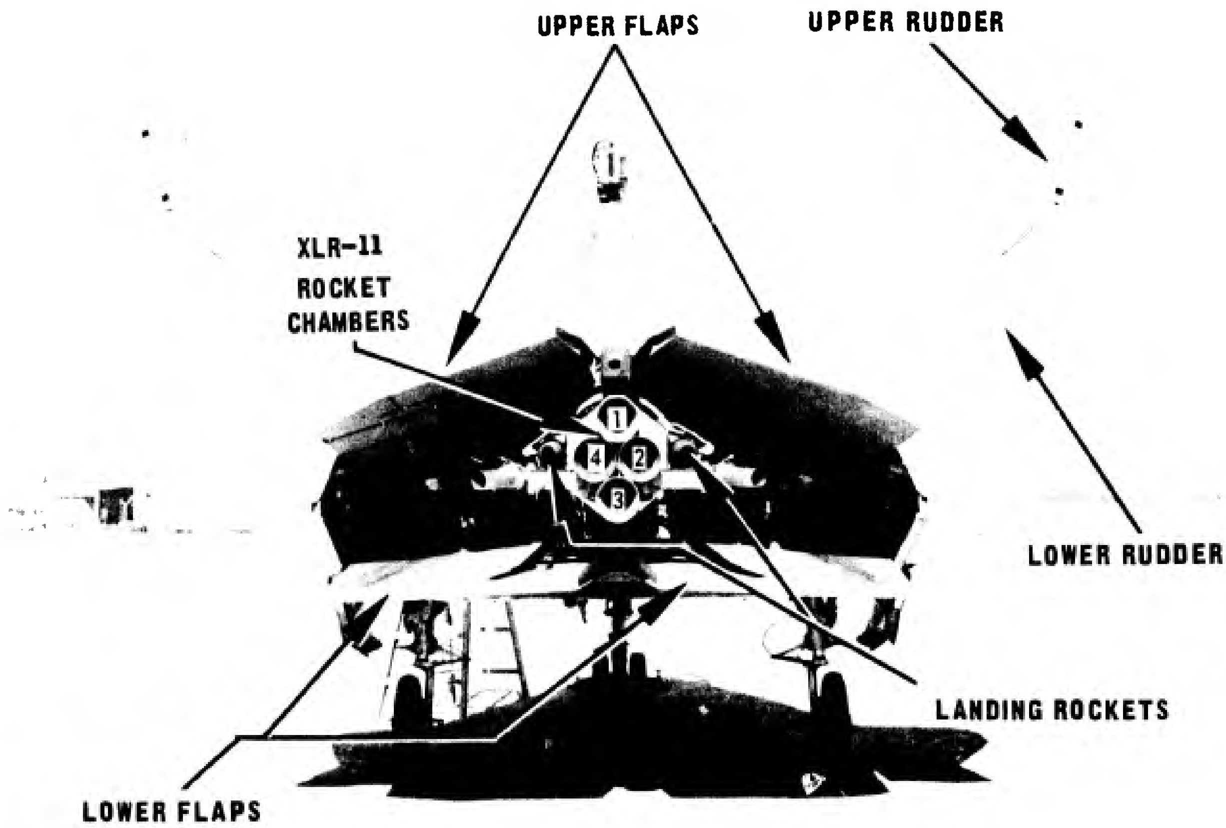


Figure 2 X-24A Control Surfaces

TEST METHODS

The X-24A was tested during an incremental Mach number envelope expansion program involving 28 free flights (reference 2). Handling qualities data were gathered using a full complement of continuously recorded stability and control parameters. The data system was a pulse code modulation telemetry system using prime and subcommutated sampling rates of 200 and 50 samples per second, respectively. A representative instrumentation parameter list is shown in reference 2.

Pilot evaluations were used as a major source of handling qualities data. A pilot questionnaire was generated before each flight, based on the flight objectives and test maneuvers planned for that flight. A postflight technical debriefing of the pilot was conducted shortly after each flight, usually the same day. During this debriefing the pilot answered the questions on the prepared flight questionnaire and supplied pilot ratings and comments wherever appropriate. A sample pilot question-

naire is shown in figure 3 (the completed questionnaire is included in appendix III). All pilot ratings were with reference to the Cooper-Harper rating scale shown in figure 4. The pilot ratings obtained during the test program are tabulated in appendix I. At the conclusion of the flight test program, two of the three pilots provided a set of overall pilot ratings of the X-24A in the configurations and flight phases which were flown on the last few flights. These ratings are identified in appendix I as "Post Program" ratings and are shown on the pilot rating plots as solid symbols.

It should be emphasized, that in most cases the pilots assigned the pilot rating reluctantly, and in some cases refused to rate a particular condition because of the short evaluation time, rapidly changing flight conditions, or operational distractions. Pilot ratings of test maneuvers to determine stability derivatives (control pulses and doublets) were not obtainable from the pilots since the test maneuvers required highly mechanical pilot actions that precluded pilot handling qualities tasks. Although pilot observation of the vehicle response to the test input was usually a good "confidence builder", pilots often commented that they would like to repeat a flight profile without the test maneuvers so they could really evaluate the handling qualities.

When specific handling qualities problems were expected or actually encountered in flight, a subsequent flight was usually flown into the same flight regime with a handling qualities task as the primary maneuver. Pilot ratings for these maneuvers are noted in appendix I by asterisks and are considered more valid than other ratings.

In order to obtain comparative data on the individual effects of flap bias, interconnect ratio, Mach number, etc., the flight test program was conducted using primarily the manual control system modes. As flight test handling qualities and aerodynamic data were gathered and analyzed, the automatic control laws were altered and improved, but were never used extensively in flight other than to confirm satisfactory operation of the automatic system.

A fixed-base, six-degree-of-freedom simulator was used for flight planning and pilot training. It was also used to establish the predicted controllability boundaries and to perform parametric studies with stability derivatives and control system features. Pilot comments after a flight were often evaluated and confirmed through the use of the simulator. During the course of the flight test program, the simulated aerodynamic data were periodically updated, based on flight test derived stability and control derivatives.

Digital computer programs were used to perform mathematical analyses of the response characteristics of the X-24A. A program which solved the characteristic equation (based on flight conditions and stability derivatives) permitted analysis of the basic vehicle (SAS off) response characteristics as well as the effects of various damper gain combinations. Root locus theory (discussed in appendix V) was used to evaluate the effects of pilot transfer functions.

LAUNCH

1. Did you note any different launch transients?
2. If recovery was different give pilot rating.

ENGINE LIGHT & ROTATION

3. Discuss the trim changes associated with engine light.
4. Did the pitch control appear any different than your last flight?
5. Rate the task to maintain 17° α.
6. Comment on roll power during the rotation.

CLIMB & ACCELERATION
[Prior to Shutdown on #1 Chamber]

7. Comment on your attempt to fly a tight boost. Give pilot ratings.
8. Did you note any abrupt lateral trim changes?
9. Comment on performance differences.
10. Did you note any trim change with engine chamber shutdown?

[After Shutdown of #1 Chamber]

11. Discuss the roll power at 13° α.
12. Give pilot ratings for this period.

[After Shutdown of #3 Chamber]

13. Did you note any trim change with #3 shutdown?
14. Discuss the roll power at 10° α.
15. Discuss your clues for final shutdown.
16. Any significant trim changes with final shutdown?
17. Did you use any rudder during boost?

DATA MANEUVERS

18. Discuss the roll response observed at 5° α. Give pilot ratings.
19. Comment on aircraft response to dampers off rudder and aileron doublets at 11° α.
20. Any comments on pushover--pullup?
21. Were you aware of any trim changes with jettison?
22. Discuss the configuration change.
    a. Longitudinal?
    b. Lateral?--did you note any tendency to PIO?

PATTERN & LANDING

23. Discuss energy management during pattern.
24. Discuss the handling qualities and riding qualities. What KRA schedule was used? Give pilot ratings.

OTHER

25. Did you make any aileron or rudder trim changes during flight?
26. Discuss the increased roll breakout forces and pitch/roll harmony.
27. Were all cockpit displays, switches, pressure suit, etc. satisfactory?
28. Do you have any recommendations for changes prior to next flight?

Figure 3 X-24A Flight X-16-21 Pilot Questionnaire

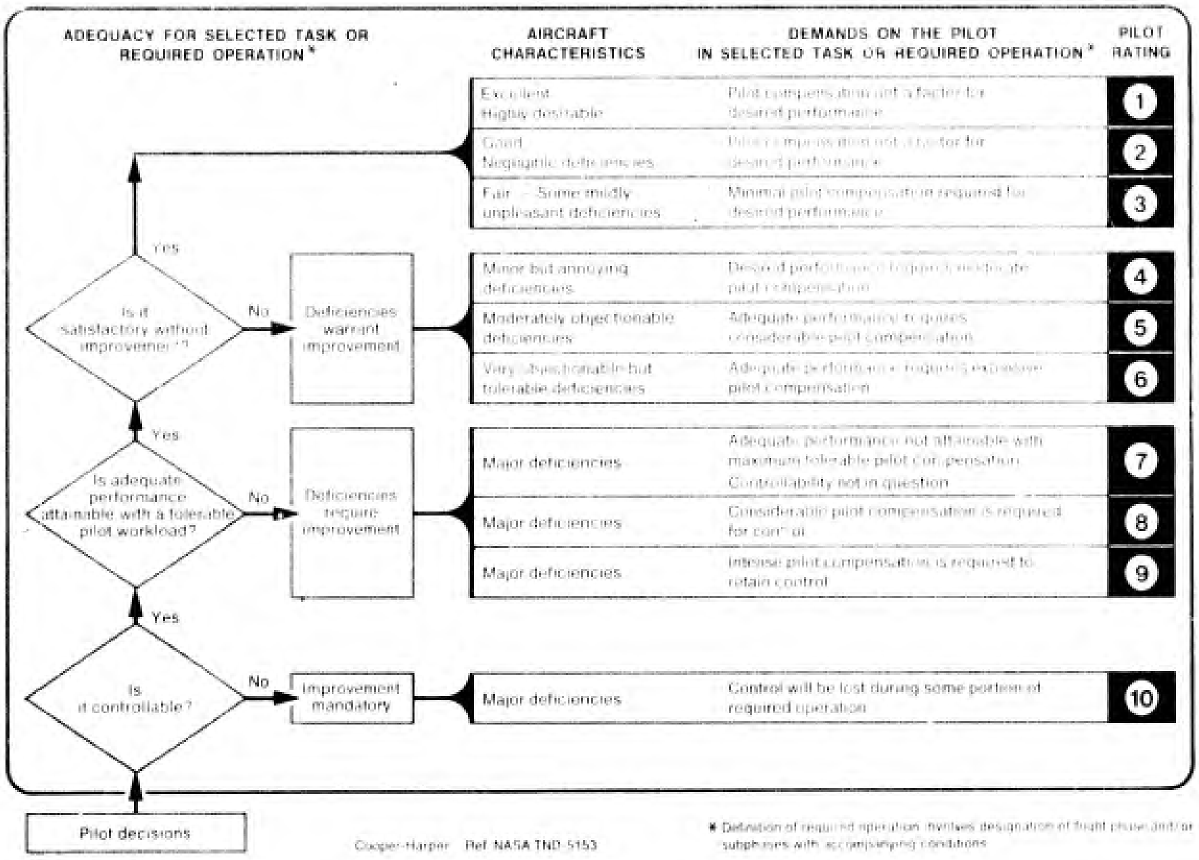
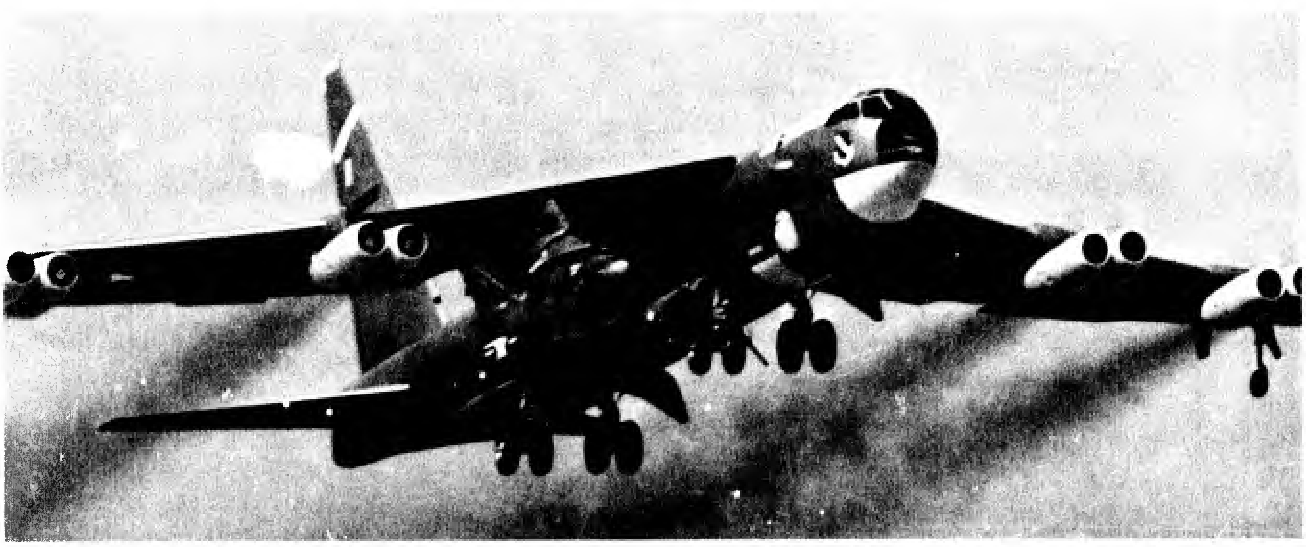


Figure 4 Cooper–Harper Handling Qualities Rating Scale



PREFLIGHT HANDLING QUALITIES STUDY

ANGLE-OF-ATTACK BOUNDARIES

Before the first flight of the X-24A, the simulator was used to establish the controllability boundaries based on the predicted stability and control derivatives.

The simulator was first flown in a qualitative manner to establish the nature of the high and low angle-of-attack boundaries. Quantitative techniques were then established to identify more precisely each boundary condition. In some cases, such as $C_{m_\alpha} = 0$ and full aft stick, the boundary condition was a reasonably well-defined line which could be identified by direct wind tunnel data analysis without use of the simulator. Other boundaries resulted from a more complex interaction of the pilot, control system, and aerodynamics.

The boundaries which were established before the first flight for the first flight configuration ($-21° \delta U_B$, $-10° \delta R_B$) are shown in figure 5. The individual factors which limited the controllability are discussed separately in the next few paragraphs.

LATERAL PIO AND ROLL REVERSAL

A lateral pilot-induced oscillation (PIO) boundary was established on the simulator by mechanizing an "automatic-pilot-roll-damper" loop.[1] This mechanization was based on the assumption (later confirmed in flight) that the pilot reacted to roll rate with lateral stick commands. This mechanization resulted in both aileron and rudder inputs through the KRA being proportional to roll rate, whereas the roll damper produced only aileron deflections proportional to roll rate. With this loop active in addition to the normal SAS loops, the angle of attack was varied slowly until an undamped lateral-directional oscillation was observed on the simulator. The boundary condition was the angle of attack for which a constant amplitude, sustained oscillation was present. The boundary value of angle of attack did not vary significantly with pilot gain; however, the rate of convergence or divergence at angles of attack above or below the boundary increased with increased gain.

Roll reversal boundaries were determined by laterally deflecting the stick, then changing the angle of attack slowly with pitch control, and noting the angle of attack at which the steady state roll rate was zero.

[1] Root locus analyses were also performed; however, the simulator technique was used for the final boundary determination since the simulator included all control non-linearities, authority limits, etc.

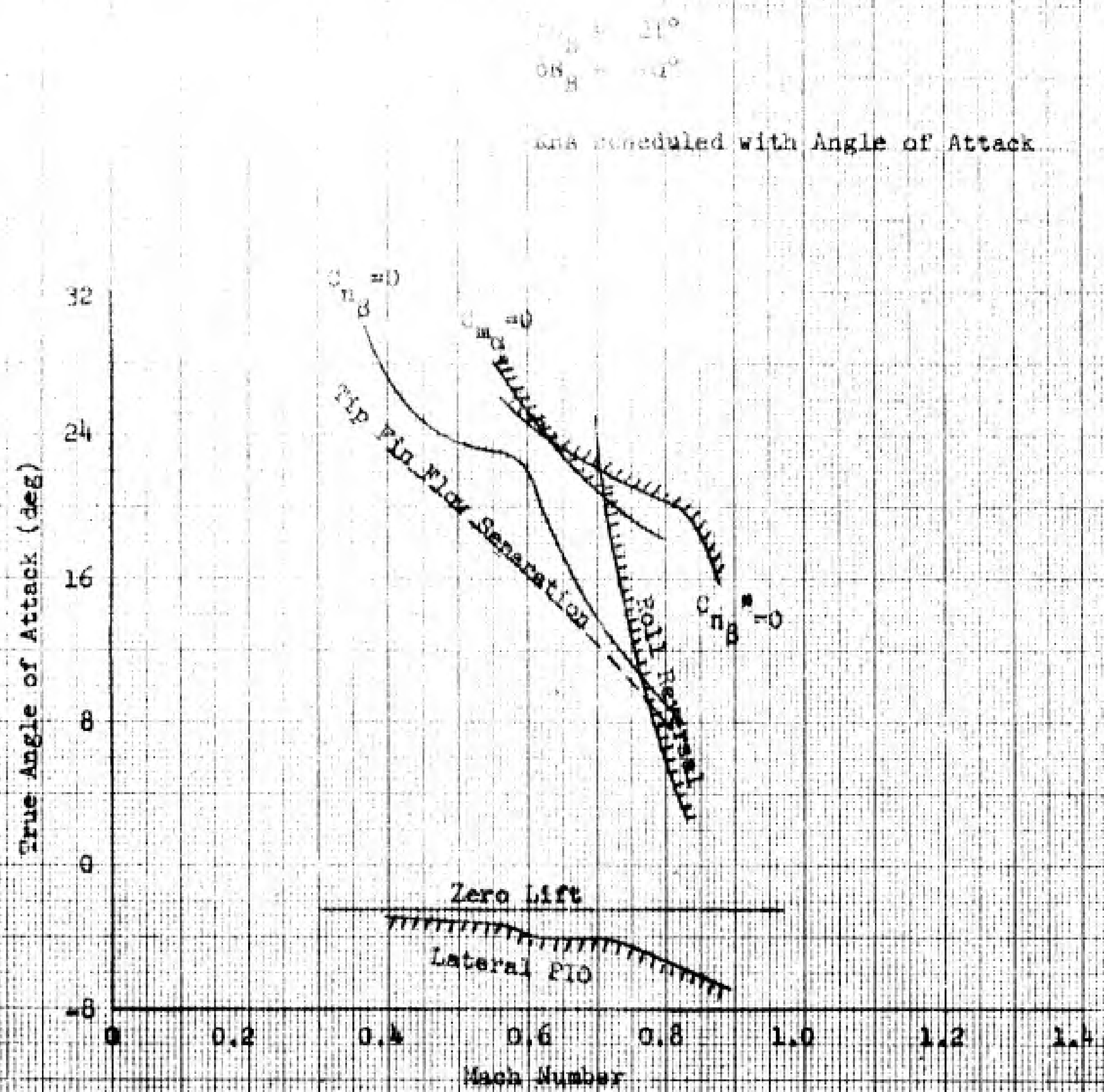


Figure 5. Predicted Flight Boundaries Before First X-24A Glide Flight

DIRECTIONAL STABILITY

Two types of directional stability boundaries were determined. A conservative boundary was established at the angle of attack at which C_{n_β} crossed zero. A second boundary was established at the angle of attack at which $C^*_{n_\beta}$ (or $C_{n_{\beta\,dyn}}$) crossed zero.[2] Simulator studies showed that, because of the high dihedral effect, the handling qualities with zero C_{n_β} were not significantly degraded with SAS on and only slightly degraded with SAS off with respect to handling qualities for positive C_{n_β}. The zero $C^*_{n_\beta}$ boundary appeared to be an absolute boundary where abrupt and uncontrolled motions occurred with SAS on or off. Between these two boundaries the vehicle was flyable with progressively degraded handling qualities as C_{n_β} decreased. Handling characteristics were much more sensitive to SAS malfunctions or improper gain settings between the two boundaries than below the $C_{n_\beta} = 0$ boundary.

SENSITIVITY STUDIES

Once the predicted boundaries were established and the nature of the boundary conditions was known, the simulator was used to perform sensitivity studies. Stability and control derivatives, as well as control system parameters, were varied in a systematic manner to evaluate the effect on the overall handling qualities and specifically the controllability boundaries.

The roll reversal and lateral PIO boundaries were found to be quite sensitive to the KRA setting. These boundaries were also sensitive to the yaw-due-to-aileron derivative, $C_{n_{\delta a}}$, and the directional stability, C_{n_β}, which were, in turn, strong functions of upper and lower flap position.

Decreasing the KRA lowered both boundaries, thus lowering the flyable angle-of-attack range, while increasing the KRA produced a flyable α range at high angles of attack (figure 6). Variations in $C_{n_{\delta a}}$ produced effects which were similar to those produced by the KRA, with proverse $C_{n_{\delta a}}$ (+) causing the same effect as the high KRA, and adverse $C_{n_{\delta a}}$ (-) the same as the low KRA (figure 7). Reducing C_{n_β} caused the boundaries to approach each other, thus shrinking the flyable angle-of-attack range. By reducing the directional stability on the simulator, it was possible to produce simultaneous roll reversal and PIO. In this situation, it was impossible to sustain a steady state roll with a constant aileron input beyond the initial transient motions (roll reversal boundary), and yet small amplitude, high frequency rolling oscillations were continually excited by the pilot in his efforts to maintain level flight (lateral PIO).

2Total lateral-directional static stability was maintained in the flight regime between $C_{n_\beta} = 0$ and $C^*_{n_\beta} = 0$ through the contribution of dihedral effect, C_{ℓ_β}. Aperiodic divergence occurred when the value of $C^*_{n_\beta}$ became negative, where $C^*_{n_\beta}$ is defined as $\frac{\omega_n^2}{I_x} = C_{n_\beta} \cos\alpha - \frac{I_z}{I_x} C_{\ell_\beta} \sin\alpha$.

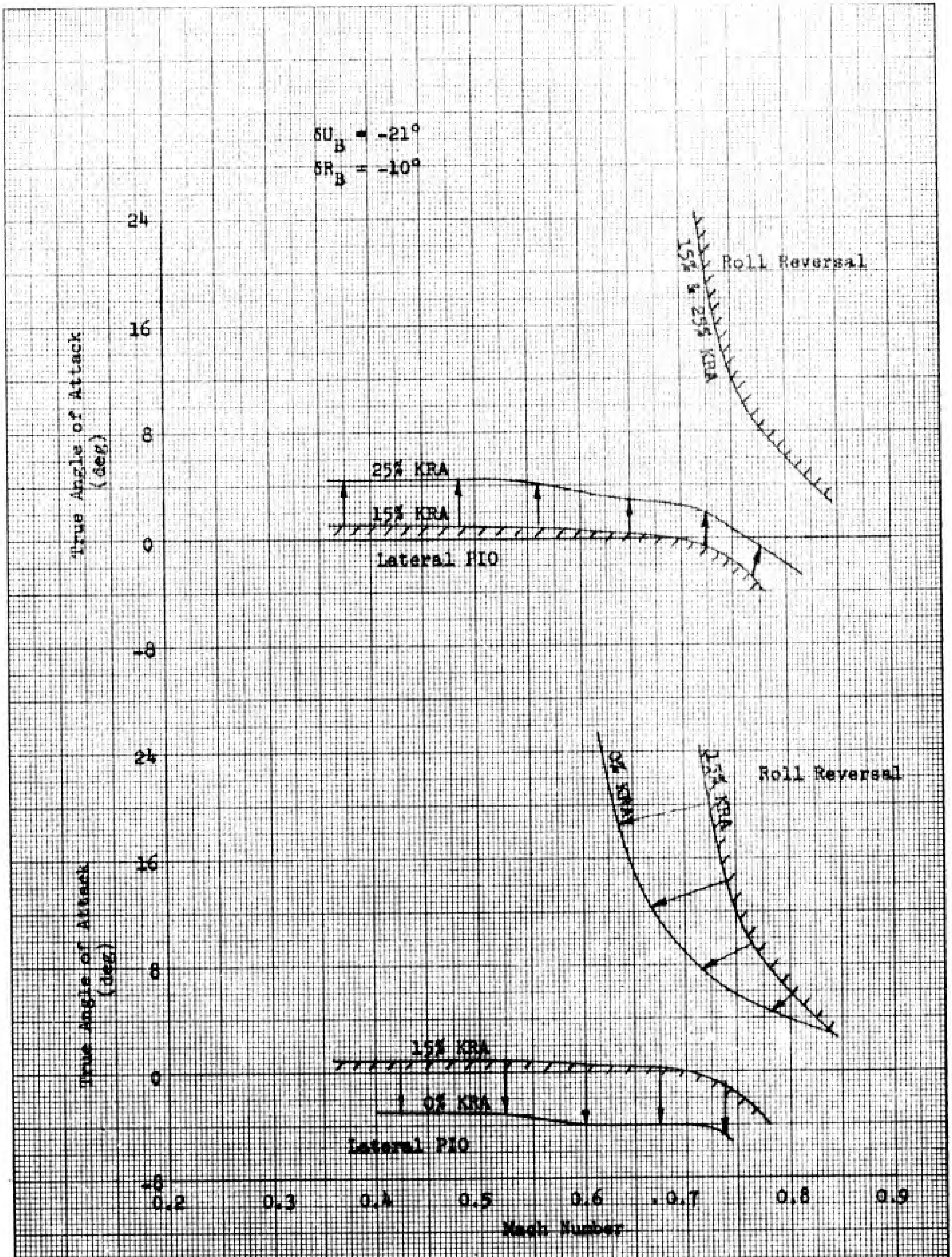


Figure 6. Effect of KRA on Stability Boundaries

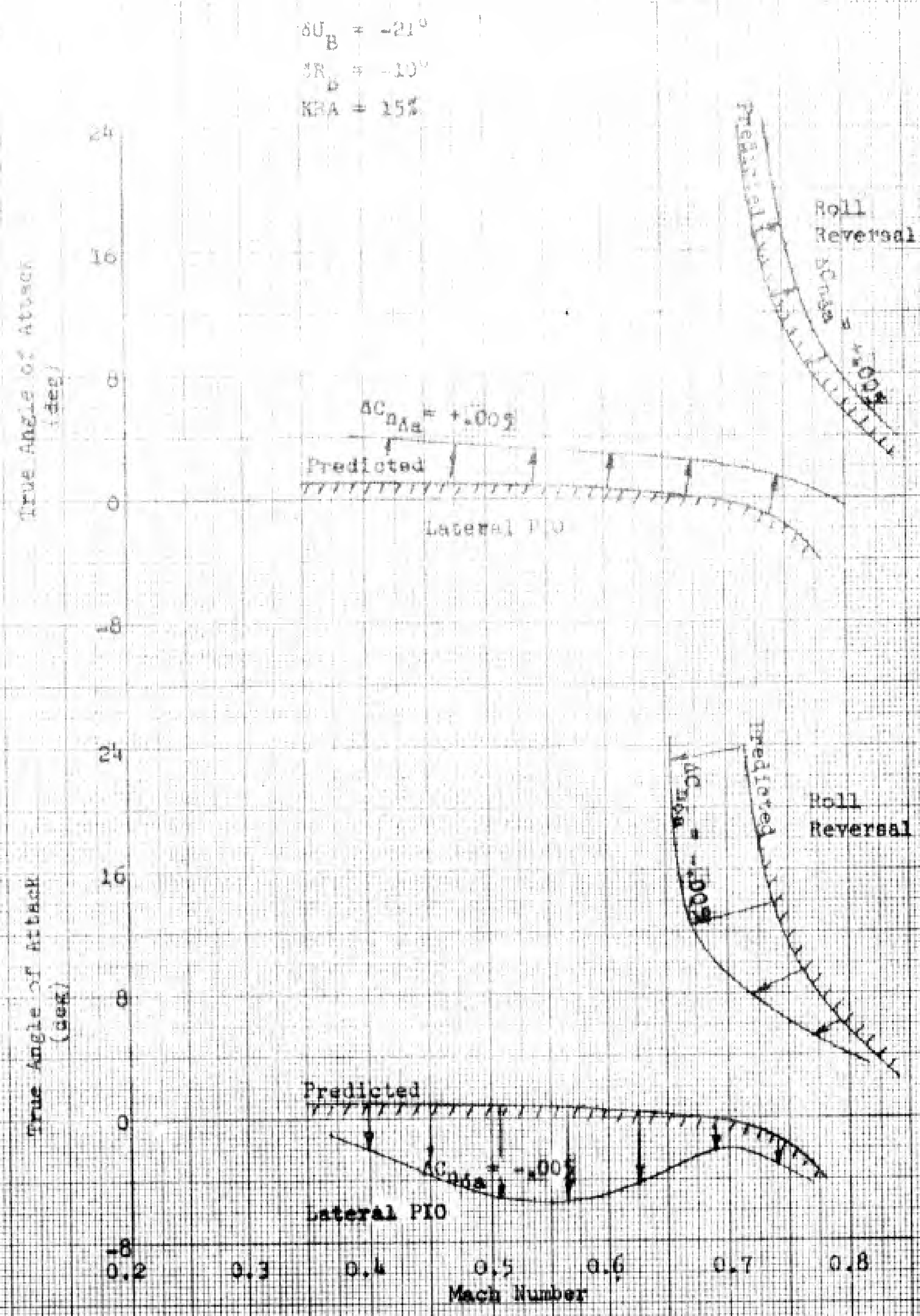


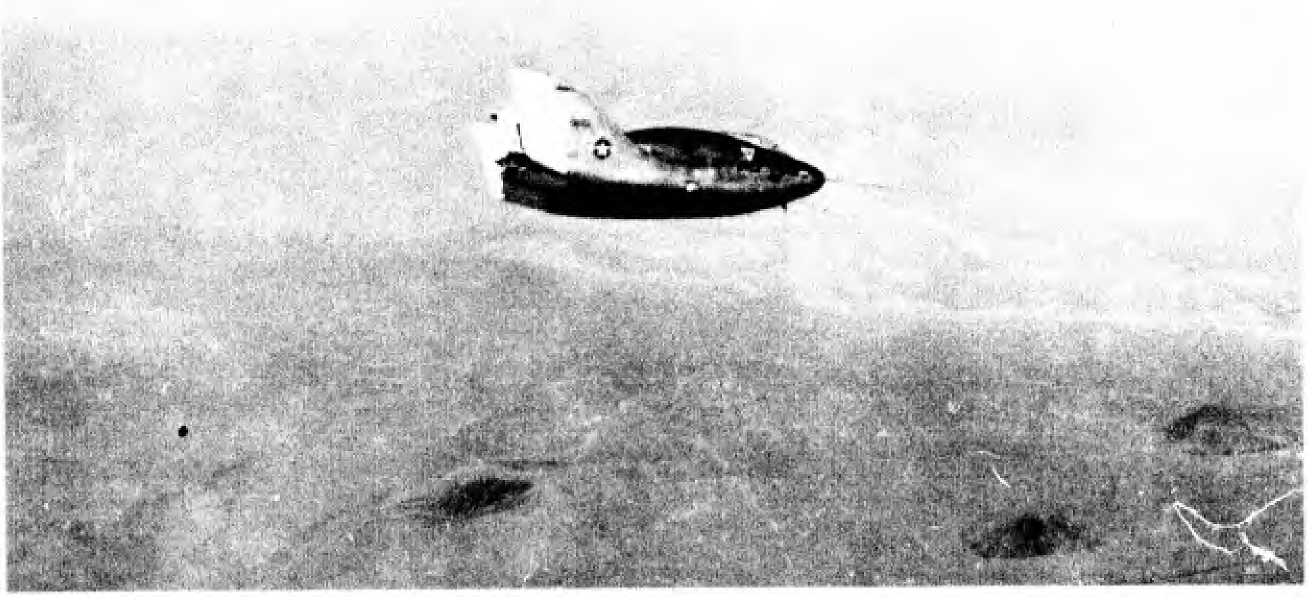
Figure 7. Effect of Errors in $C_{n_{\delta a}}$ on Stability Boundaries

APPROACH AND LANDING BOUNDARIES

It was highly desirable to have the upper and lower flaps closed as much as possible during the landing approach to reduce the base drag and thus improve the glide angle. Wind tunnel data showed that both the transonic directional stability and dihedral effect (C_{n_β} and C_{ℓ_β}) were sharply reduced as the upper flaps were closed, especially below -30 degrees (figure 8). Therefore, the controllability boundaries in the final approach and first flight configurations became considerably more restrictive in terms of Mach number (figure 9). Simulator results indicated that in the final approach configuration ($-13° \delta U_B$, gear up) the vehicle would have been totally uncontrollable above Mach 0.75.

CORRECTIVE ACTION

The simulator was also used to determine the pilot cues or handling peculiarities that signaled an approach to these boundaries. Optimum pilot corrective action was also determined in the event that these boundaries were exceeded inadvertently. The roll reversal characteristic was relatively mild, with adequate warning consisting of reduced roll power. Depending on the situation, the pilot corrective action was either to reduce angle of attack, increase the value of KRA, or use the rudders. The lateral PIO characteristic was potentially more violent and less accurately predicted from the fixed base simulator. The warning was in the form of increased roll sensitivity for small rolling motions and the pilot corrective action was to increase the angle of attack and reduce the KRA if motions persisted. Simulator studies showed that there was very little warning as the $C^*_{n_\beta} = 0$ boundary was approached, and divergence occurred abruptly. This boundary was carefully avoided throughout the program.



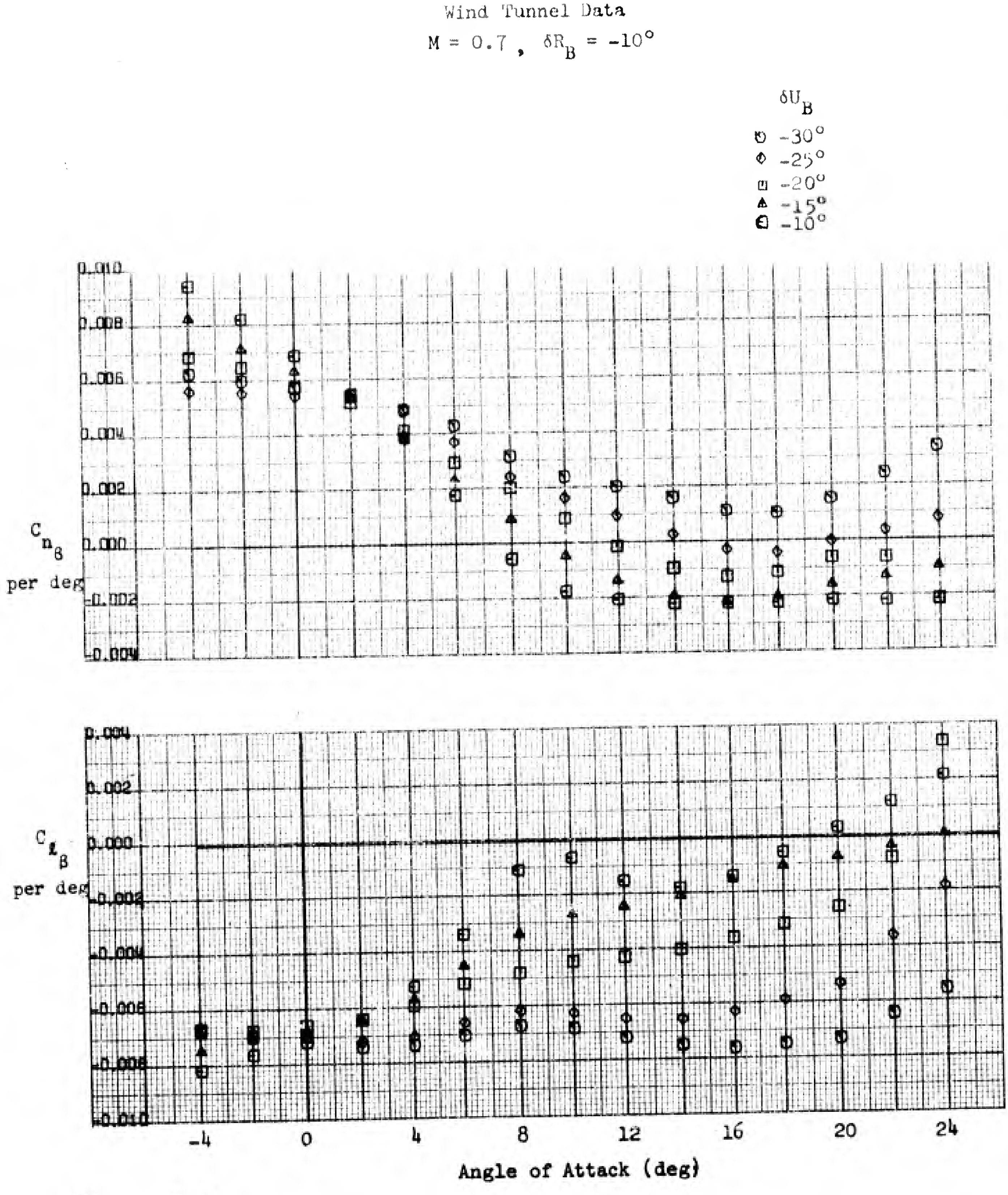


Figure 8. Lateral-Directional Stability Variation with Upper Flap Position

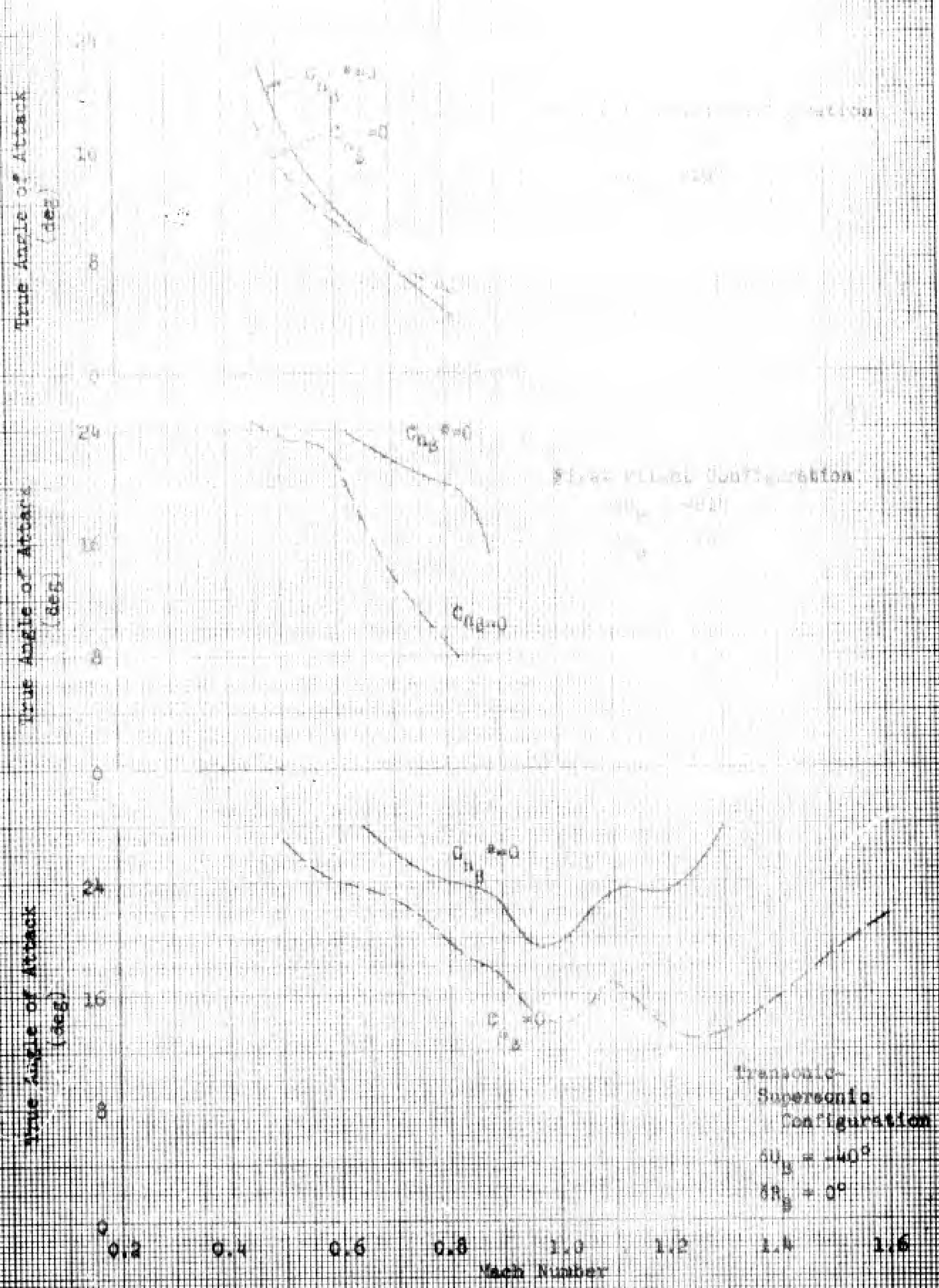


Figure 9. Effect of Upper Flap Bias on Predicted Stability Boundaries

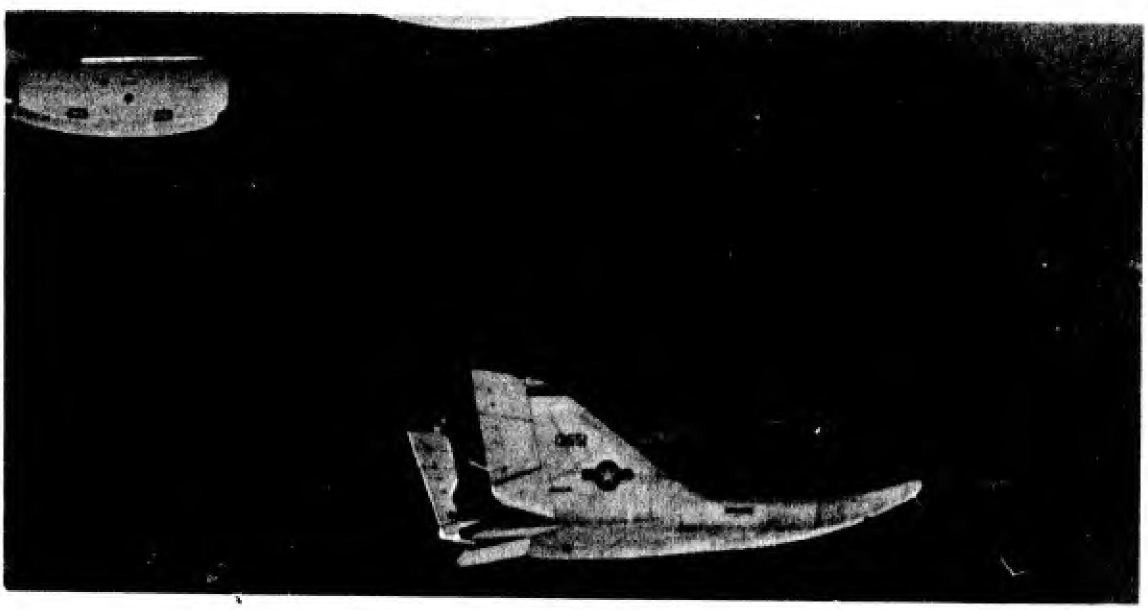
FLIGHT TEST HANDLING QUALITIES

GENERAL

At the conclusion of the program, the X-24A test pilots observed that the vehicle in its final configuration exhibited three distinctly different levels of handling qualities associated with three phases of flight: (1) approach and landing, (2) transonic, and (3) supersonic. The following is a direct quote from a pilot after he had flown one glide and nine powered flights in the X-24A:

> "We have levels of stability on the airplane and they're just as clear cut as night and day. You can feel it when you go from one level to another. One level is in the fairly low subsonic level, and this is very good. The airplane flies beautifully in this area. In the area from 0.80 to 0.95 or so, we have another level of stability. This is probably the worst area stability wise. The airplane moves around a lot, and it never seems to settle down. Then once you go beyond Mach one, or up in that area, why, the airplane smooths out. You can feel it and almost hear it. You can just sense these three distinct changes in stability."

The handling qualities in the approach and landing phase in the final configuration were described as quite responsive, well-behaved, and easy to fly; they were compared favorably with those of a modern fighter aircraft. In the transonic phase, the vehicle was considerably looser in all axes, difficult to fly precisely, and prone to spurious lateral and longitudinal trim changes; it generally required a great deal of pilot attention. Although only a small amount of flight time was accrued at supersonic speeds, the vehicle was described as being quite solid and stable, with low but adequate control response.



In the following sections the handling qualities of the X-24A are discussed in approximately the sequence of their occurrence during a typical powered flight. A typical powered flight sequence was as follows:

Transonic Phase	Launch	-	Release from the B-52, followed by ignition of the rocket engine.
	Rotation	-	A constant angle of attack subsonic acceleration and climb to attain a desired climb angle.
	Climb	-	A constant pitch angle subsonic climb (typically 40 degrees θ, 0.8 to 0.9 Mach number).
Supersonic Phase	Pushover	-	A low angle of attack acceleration at less than 1 g to attain supersonic speeds.
	Glide	-	Deceleration and descent after engine shutdown while performing test maneuvers and energy management.
Approach Phase	Configuration Change	-	Resetting of the flap and rudder bias system to the landing configuration below 0.6 Mach number.
	Approach	-	A 180-degree descending turn ending with a high energy final approach.
Landing Phase	Flare and Landing	-	A flare to level flight followed by landing gear extension and landing on Rogers Dry Lake.

LAUNCH

Simulator studies and digital computer studies using wind tunnel data from a 2.5-percent scale model were used to analyze the effects of the B-52 flow field on the X-24A motions at launch. These studies showed that bank angle excursions of 20 to 30 degrees could be expected during normal launches. Although the motion trends actually experienced with the vehicle were similar to those observed in these studies, the magnitudes of the motions were consistently less than predicted. Launch pilot ratings are shown in figure 10. The piloting task was to recover to wings-level flight at a constant angle of attack. Pilot ratings of the simulator launches (which used the wind tunnel data) were 3 in pitch and 3.5 to 4.5 in roll-yaw. Post-program summary pilot ratings for the launch by two of the X-24A pilots were 2 to 3.5 for pitch and 2 to 3 for roll-yaw. Pilots commented that the disturbance associated with the X-24A launch was mild with only slight differences between the heavy- and light-weight conditions, and that the recovery to level flight was easy and quick. The various launch conditions which were used during the program are shown in figure 11.

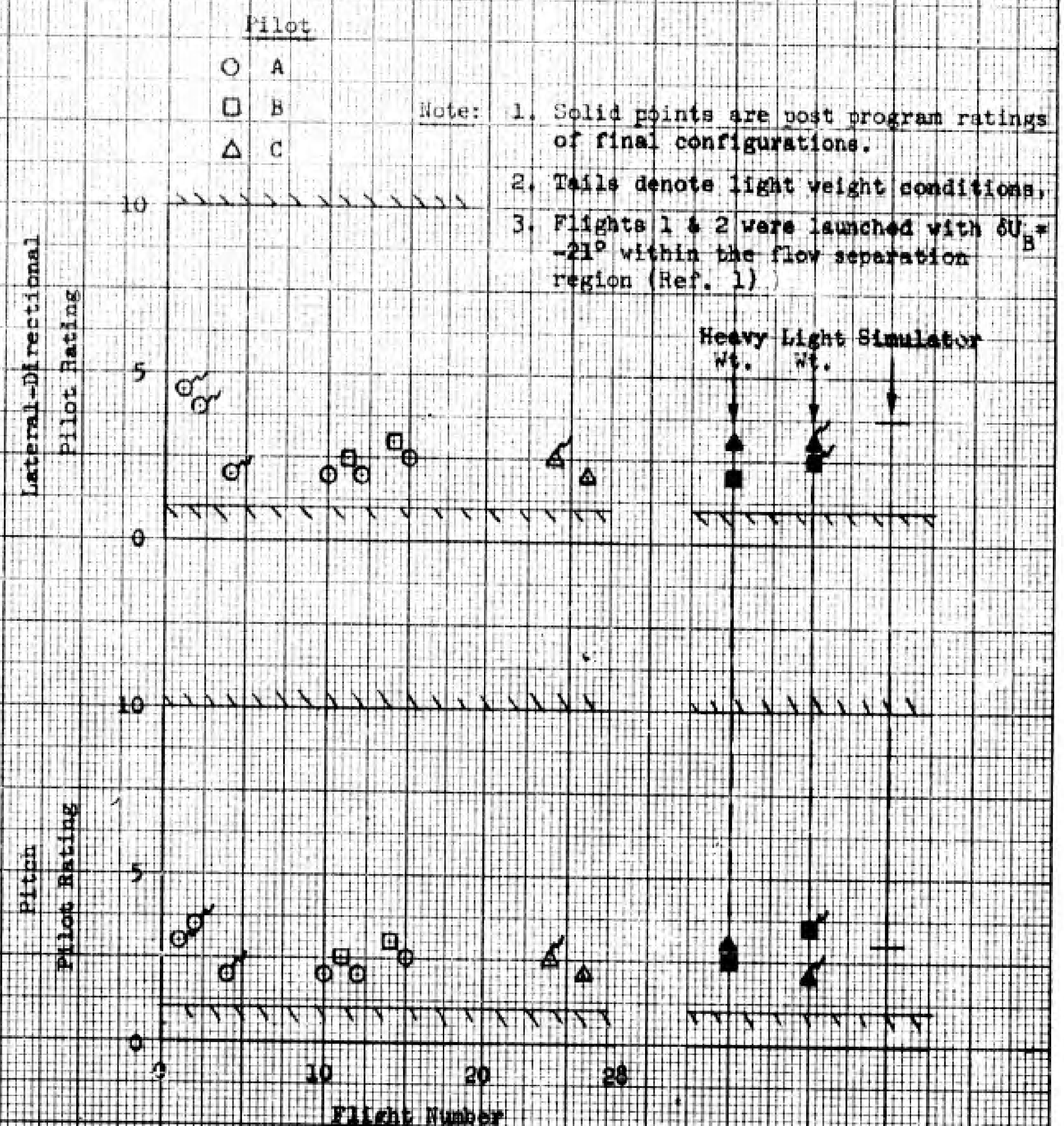


Figure 10. Pilot Ratings for X-24A Launches

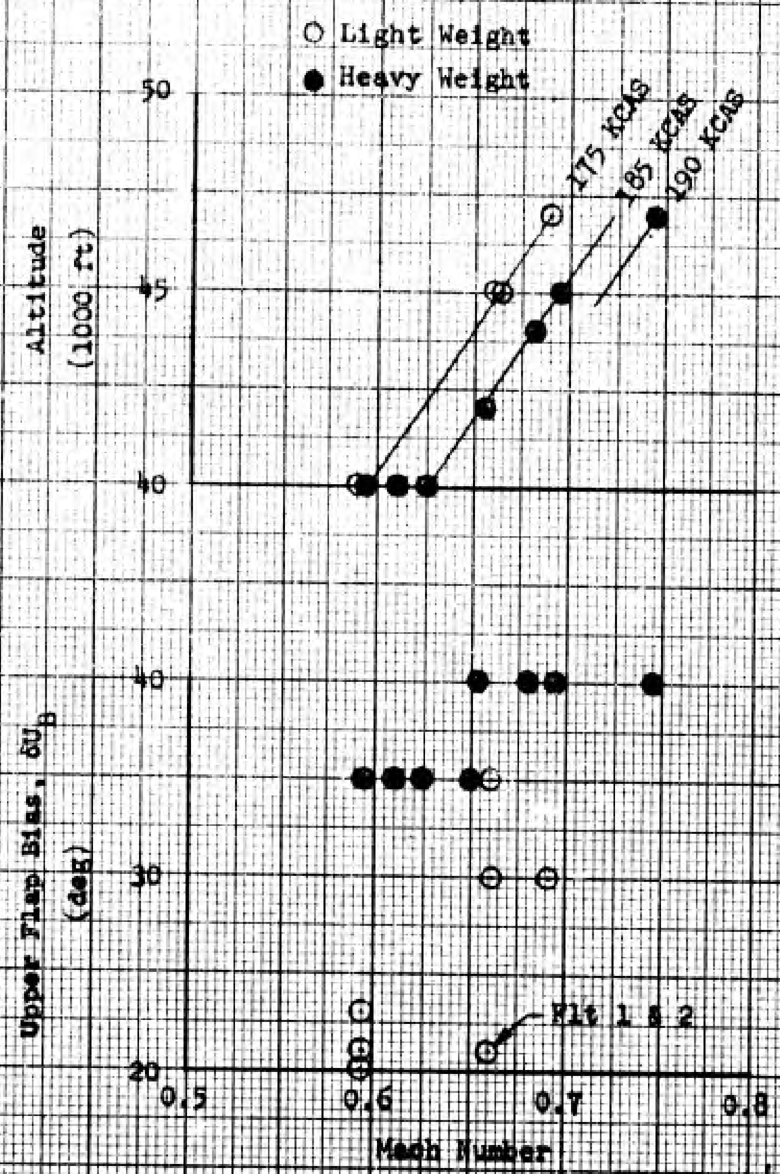


Figure 11. X-24A Launch Conditions

TRANSONIC PHASE (Mach 0.6 to 1.0)

The transonic handling qualities of the X-24A were dominated by the effects of flow separation on the tip fins and low values of static longitudinal and directional stability. The vehicle was prone to continual disturbances in this flight regime and required a great deal of pilot attention to fly precisely.

Configurations Flown

The configurations and transonic flight envelope flown during the test program are depicted in figures 12 and 13. Changes to the upper flap bias, rudder bias, interconnect ratio, and SAS gains were tried during the program in an attempt to improve the transonic lateral-directional characteristics; only limited success was achieved. Operational considerations dictated that the powered portion of each flight be flown at relatively high angles of attack (11 to 18 degrees). The precision with which the boost profile was flown was critical to attaining the objective flight conditions; therefore, few test maneuvers were requested of the pilot during this phase.

The transonic glide phase of each flight was characterized by nearly constant dynamic pressure, but rapidly decreasing Mach number. Therefore, test maneuvers and pilot evaluations were necessarily short and covered highly transient conditions.

Longitudinal Handling

The longitudinal handling characteristics of the X-24A in the transonic flight regime were generally well-behaved. Short period frequency and damping were adequate for all configurations flown. The SAS-off characteristics in pitch were better than anticipated due to the higher-than-predicted level of inherent damping (reference 5). The predicted pitching moment curves showed lower levels of static stability at the higher angles of attack with a mild pitchup predicted at 20 degrees angle of attack at 0.85 Mach number. Flight data from pulses at low to medium angles of attack confirmed this trend (figure 14). Pilot ratings of the rotation and climb showed some slight degradation in longitudinal handling as the airspeed decreasing during the climb (figure 15). Pilot comments were that the vehicle was difficult to trim in pitch during the rotation and required constant attention for precise control. The following quotation is a typical pilot comment:

> "I think the simulator may be a little bit sensitive, but the airplane does exhibit this very sensitive tendency up in this alpha range at this time. It's a pretty sensitive airplane. It's very difficult to hold a real solid angle of attack - it moves around quite a bit within this plus or minus 1-1/2 to 2 degrees."

Significant differences were observed between the power-on and power-off longitudinal trim curves (figure 16). Analysis showed that these differences took the form of a constant, nose-up pitching moment increment which was present whenever one or more chambers of the rocket engine were running. The magnitude of the pitching moment was considerably larger than would be predicted by the thrust line offset with respect to the

measured vertical cg, and has been assumed to be an aerodynamic effect produced by the rocket exhaust plume. Although this trim change was not large enough to compromise flight safety, it was not anticipated before flight and therefore was a surprise to the pilot on the first powered flight (flight 10). Prior to flight 15, a flight control system adjustment was made to increase the lower flap bias travel and thereby increase the forward elevator travel available to the pilot. This was necessary to allow the pilot to compensate for the engine trim change during the push-over at high altitude and low dynamic pressure where the effect was most significant. On three flights, small but abrupt trim changes occurred during the rotation while the engine was running. These trim changes occurred in pairs which bracketed the peak Mach and dynamic pressure during the rotation. Subsequent data analysis showed that the incremental pitching moment attributed to the rocket plume effect abruptly disappeared at the first trim change as the Mach number and dynamic pressure ($\bar{q}$) were increasing, then abruptly reappeared as the Mach number and $\bar{q}$ decreased through the same values. The longitudinal trim curves between these two trim changes were the same as the power-off trim curves. This period of the flight also corresponded with the minimum altitude during rotation. The effect may be related to static pressure and to the under-expanded rocket nozzle (design altitude of 27,000 feet).

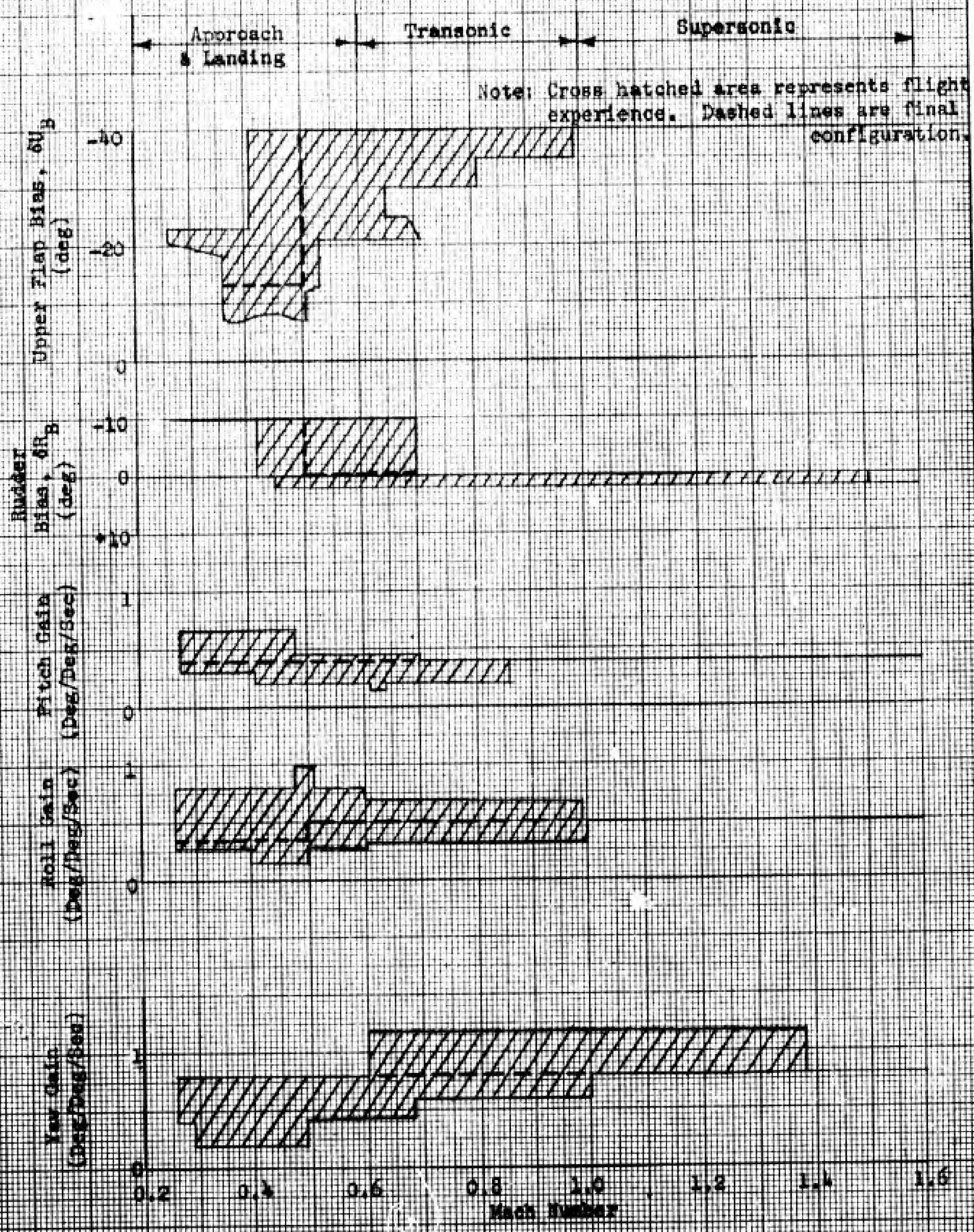


Figure 12. Control System Configurations Flown

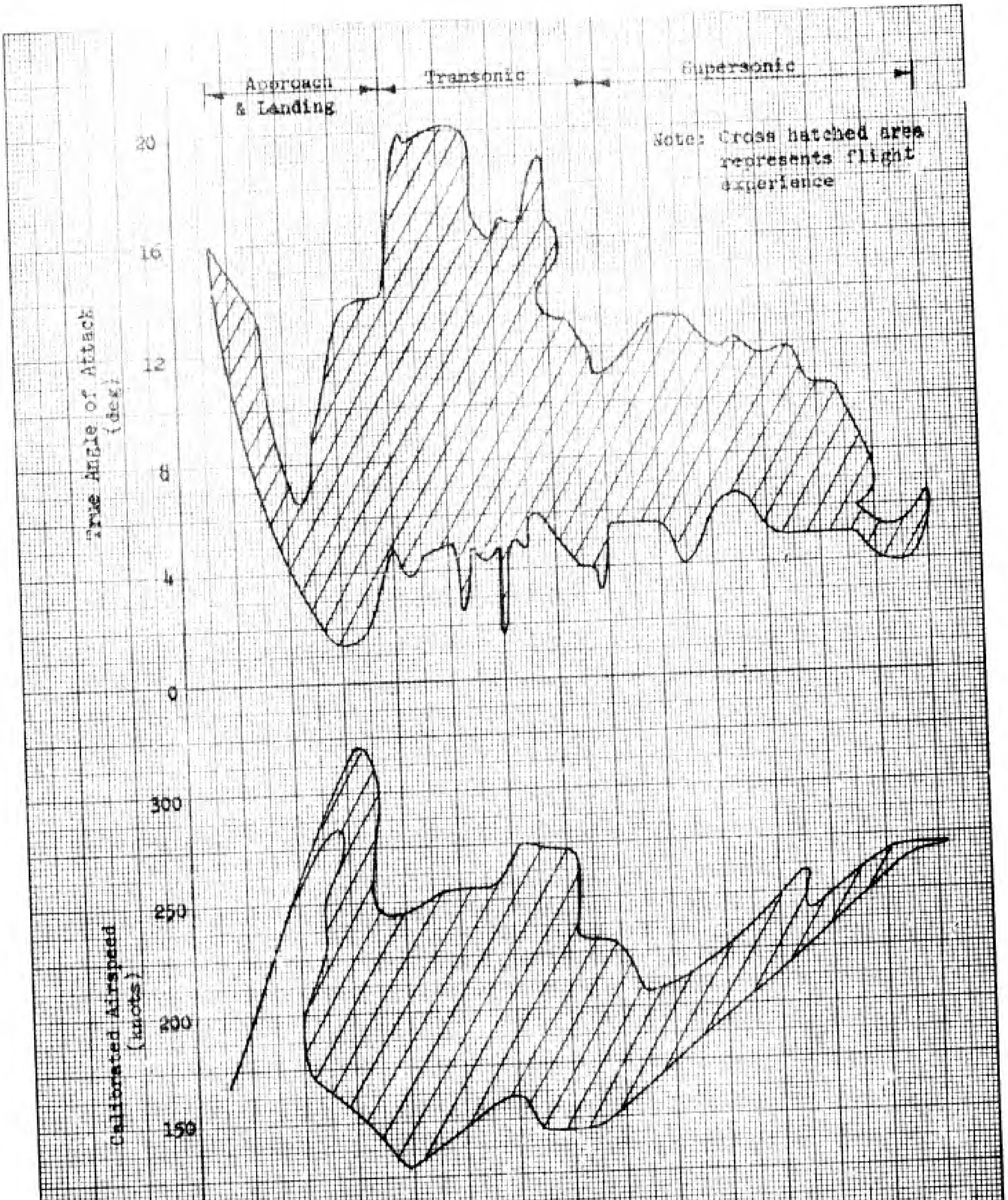


Figure 13. X-24A Flight Envelope Flown

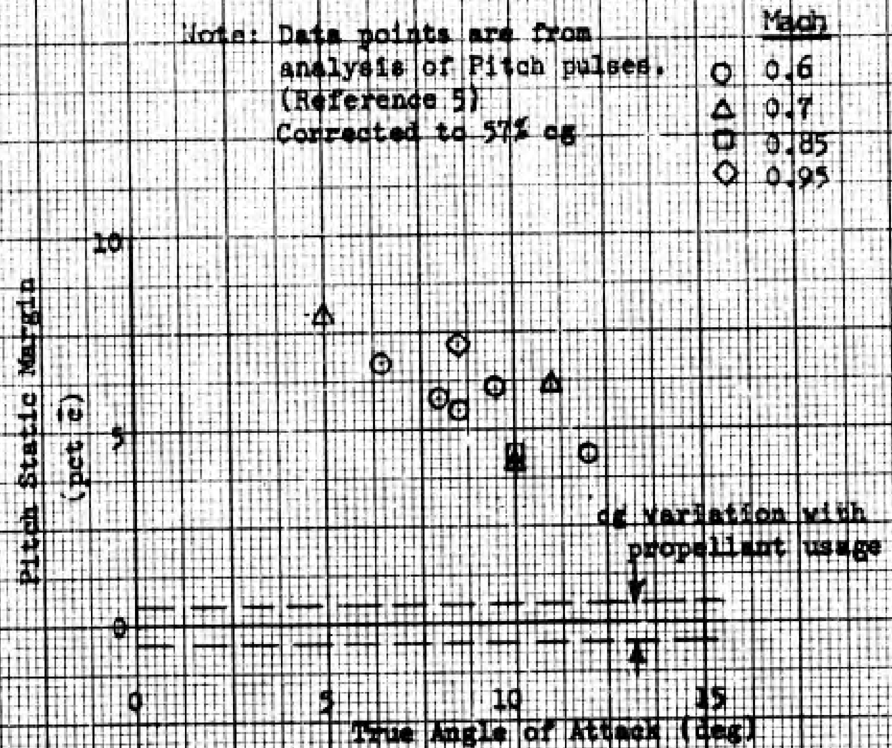


Figure 14. Transonic Static Margin

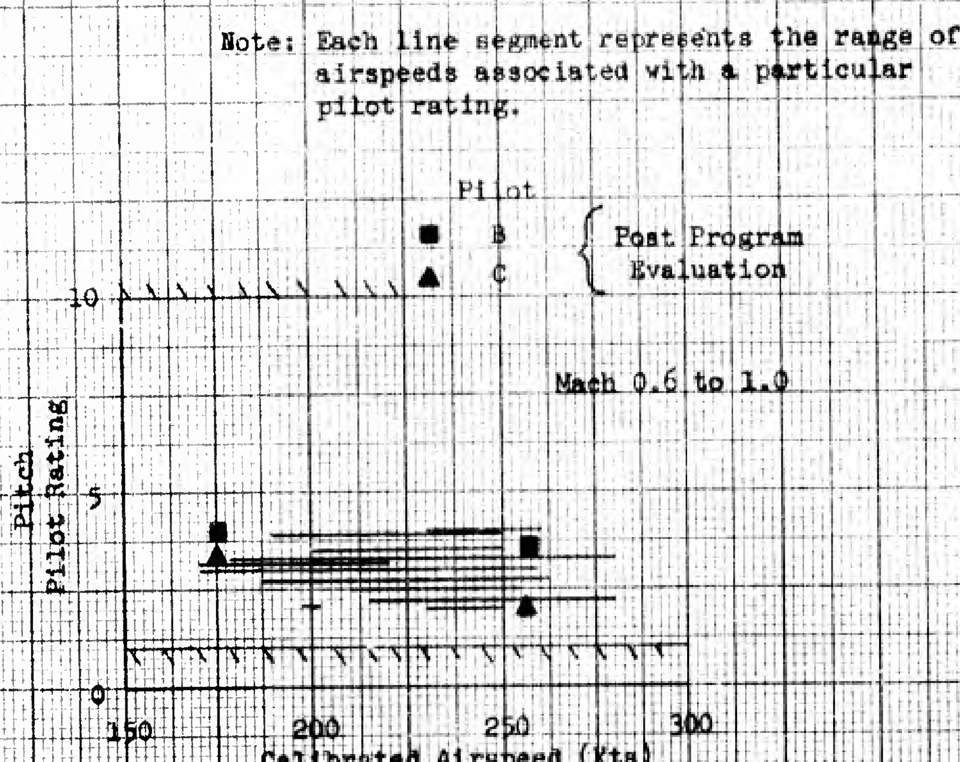


Figure 15. Pitch Pilot Ratings - Transonic Boost

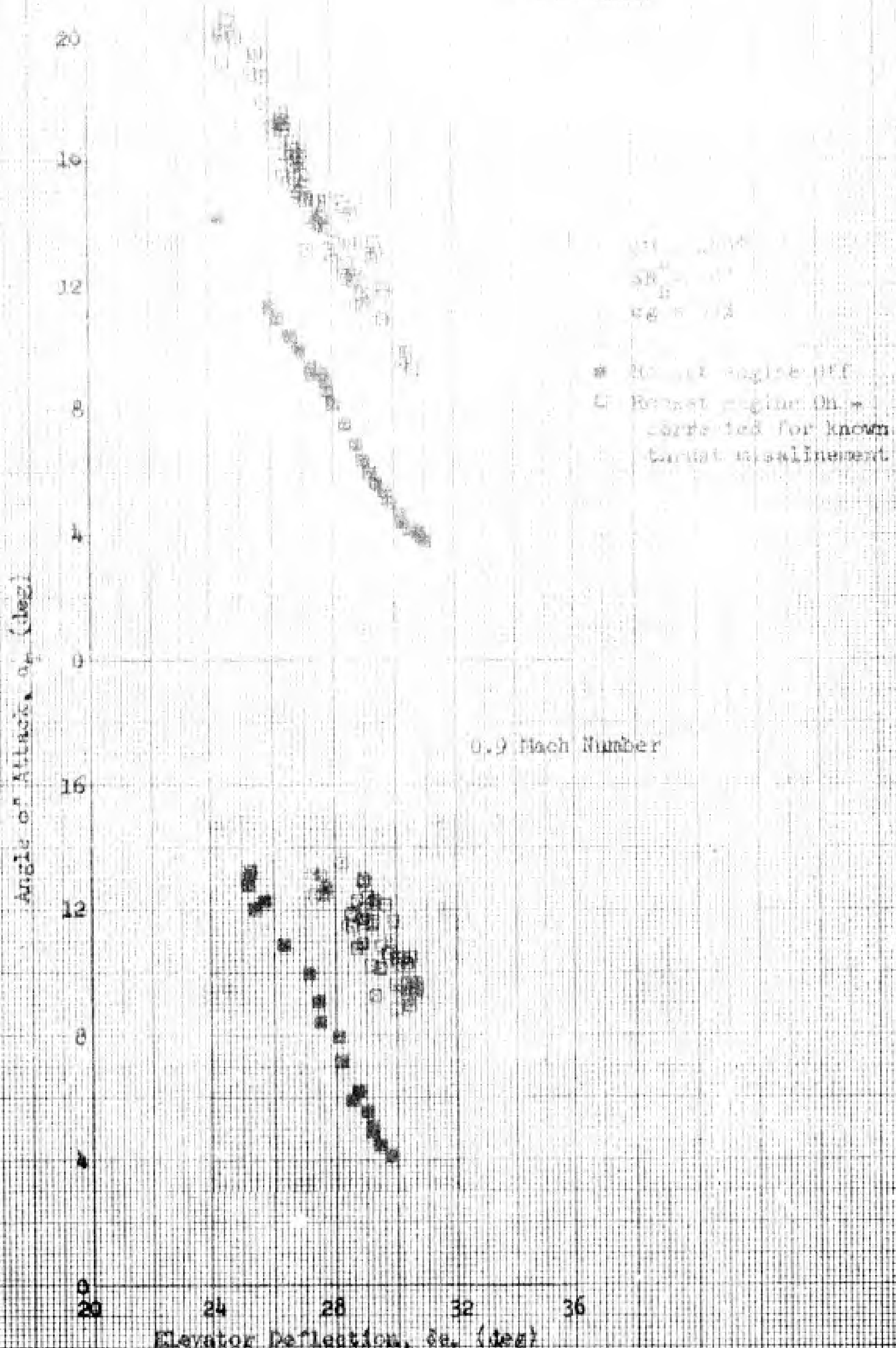


Figure 16. Effect of Rocket Engine on Longitudinal Trim

Lateral Directional Handling

Early Glide Flights

During early glide flights, at 0.6 to 0.7 Mach number in the -21-degree upper flap, -10-degree rudder bias configuration and mid angle of attack range (4 to 10 degrees), lateral trim changes with changes in angle of attack were observed. During the course of the glide flight program, a known warp in the left upper flap was corrected, upper flap and rudder bias settings were increased, and several internal control system changes were made. On flight 9, the last glide flight before powered flights, the pilot observed that he did not experience a noticeable lateral trim change while performing a pushover-pullup maneuver. The lateral trim change with angle of attack was not mentioned by the pilots on any subsequent flights and was most probably caused by the warped left upper flap.

During early glide flights, pilots also had difficulty in establishing stable trimmed flight in the 0.6 to 0.7 Mach region and complained of random lateral disturbances and/or random changes in lateral sensitivity at essentially constant angle of attack. Subsequent data analysis showed that this Mach/angle of attack region was along the boundary of vortex impingement or separated flow, on the tip fin (reference 1).[3] The poor lateral handling qualities were possibly a result of asymmetric vortex impingement on the right and left tip fins.

Boost

Although the lateral-directional handling qualities during the transonic boost phase were adequate for a research mission, a great deal of pilot attention was required. Throughout the program, the pilots reported spurious rolling motions during the boost phase that they were unable to associate with any pilot action or flight condition. Although these spurious inputs were small and easily controlled, they were disconcerting to the pilot. A typical pilot comment follows:

> "The airplane moves about in roll a bit more than the simulator does. Here again it seems like a spurious-type roll input. During this roll control it is just a little bit non-linear. I don't understand it at all. Quite rapid response with small stick deflections, and it becomes smaller as you get the stick away from neutral position."

Notice that this comment confirms the trends observed on the simulator with reduced Cn_{β} and is indicative of a situation approaching a simultaneous PIO and roll reversal (refer to the Sensitivity Studies section). It is felt that these motions were possibly associated with the unsteady flow over the tip fins while operating above the vortex impingement (flow separation) boundary or small lateral upsets produced by horizontal wind shears during the climb. Small amplitude, lightly damped lateral motions

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[3]Further study of tip fin photos subsequent to the publication of reference 1 indicated that the phenomenon was probably not strictly flow separation, but was probably associated with impingement of the body vortex on the inner tip fin surface, which created an abrupt change in flow direction from chordwise to spanwise prior to total flow separation. The effect was the same in either case, an abrupt partial loss of lift on the tip fins.

were usually present throughout the subsonic phase of powered flight (figure 17). Pilot lateral stick activity was observed during these oscillations which consistently opposed roll rate. The amplitudes of these lateral motions increased as the dynamic pressure decreased during the climb. Pilot ratings and comments also reflected the "loose" nature of the vehicle handling in the lateral axis at low dynamic pressure with the rocket on (figure 18). A root locus plot[4] using the flight test stability derivatives (appendix II) and a $\delta a/P$ pilot gain is shown in figure 19. Note that increasing pilot gain increased the frequency and decreased the level of damping, while lowering the dynamic pressure tended to reduce the overall damping and frequency regardless of pilot activity. The spurious roll inputs combined with a low level of Dutch roll damping and the ineffective pilot efforts to damp the oscillations resulted in somewhat worse pilot ratings in this area than in other flight regimes. Figure 20 shows the effect of yaw and roll damper gains on the location of the Dutch roll pole at the rotation angle of attack. Since Cn_{β}, was negative or destabilizing at this angle of attack, it followed that the yawing acceleration due to sideslip and resulting measured yaw rate were opposite in sign to those of a statically stable vehicle. As a result, an increase in the yaw damper gain for this condition was destabilizing and tended to reduce the Dutch roll damping. The ailerons, and thus the roll damper, were relatively ineffective at this condition and an increase in the roll gain produced only a small improvement in damping. To provide some artificial static stability in this flight regime, a lateral accelerometer was installed and the output added to the yaw rate feedback in the yaw axis (a_y feedback).

As a result of simulator studies, the lateral accelerometer was located as far above the vehicle centerline as possible to take advantage of the phasing and increased gain produced by the roll acceleration of the vehicle. The a_y feedback system was strictly a breadboard installation used only during the boost portion of flight. The change to the Dutch roll pole location with the SAS only and SAS plus a_y feedback is seen to provide a small increase in frequency and damping of the Dutch roll mode (figure 20). The system was installed late in the test program and was activated for a short time during each of the last three flights. Unfortunately rocket engine problems precluded a good evaluation of the a_y system in the area of negative Cn_{β}. In the stable flight regime there was no noticeable change in handling qualities with the a_y system on.

During the test program, the flight test values of Cn_{β} in the transonic Mach range were determined to be lower than predicted. Simulator studies with the reduced values of Cn_{β} identified a low angle of attack roll reversal boundary which had not been present in earlier studies (refer to the Confirmation of Handling Qualities Boundaries section). At the completion of the climb phase, but before engine shutdown, a pushover to low angle of attack was performed to allow the vehicle to accelerate to supersonic speeds. A rapid pushover by the pilot at 0.9 Mach number caused the angle of attack to approach the roll reversal boundary and this resulted in rather large amplitude, low frequency rolling motions

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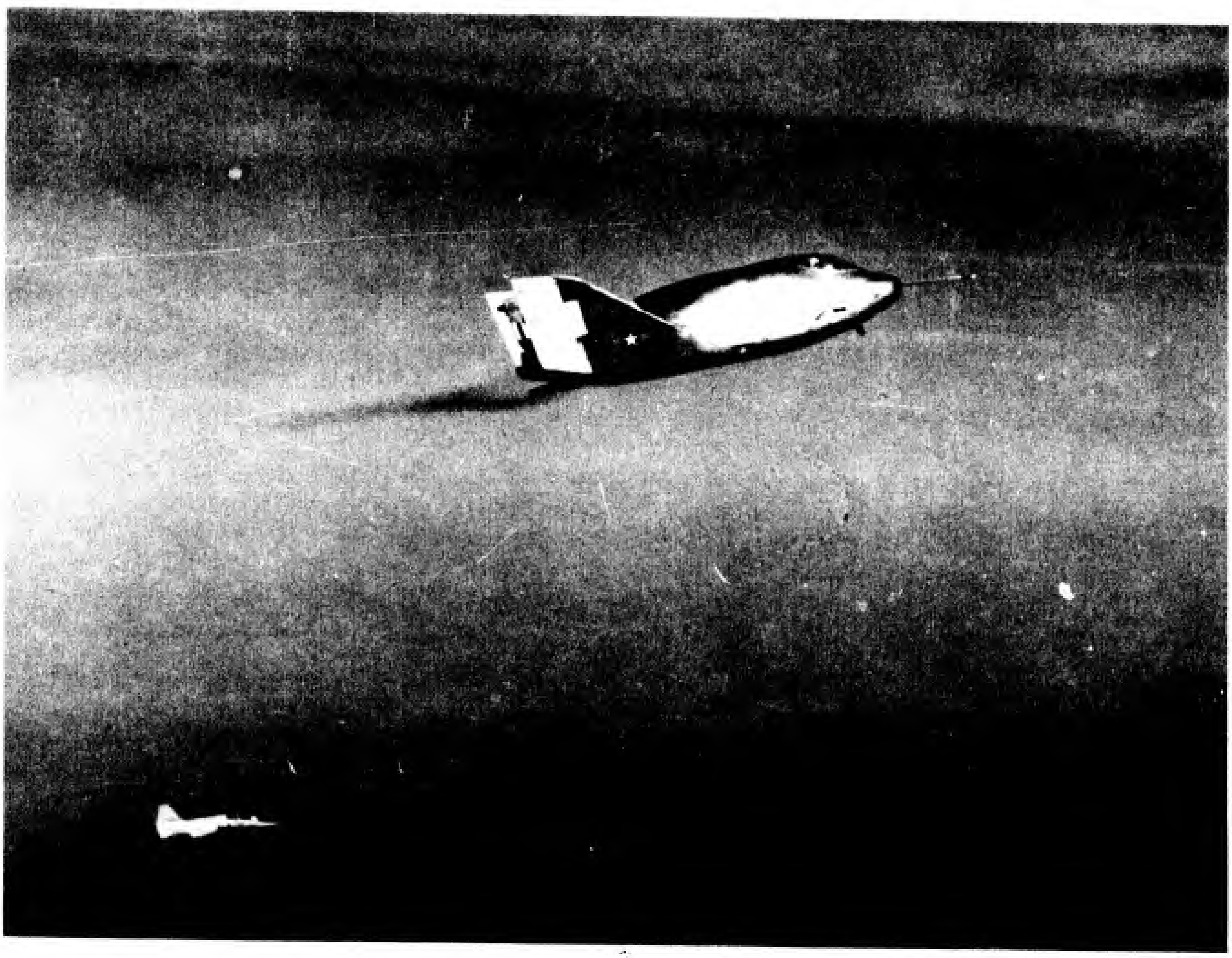
[4]A brief discussion of root locus theory and the analysis and presentation techniques used in this report is included in appendix V. Whenever root locus and simulator results were compared, the simulator showed slightly less damping. This was attributed to the more accurate simulation of control system deadbands and non-linearities in the simulator.

while the vehicle was accelerating through Mach 1.0 (figure 21). A two-step pushover was used on later flights (reference 2) which placed the angle of attack midway between the two boundaries, and the KRA versus α schedule was modified to improve the roll power at low angle of attack.

Thrust asymmetry was experienced on one flight when two of the four rocket chambers failed to start. The location of one of the two operating chambers (No. 4) being displaced laterally from the cg approximately 3.6 inches (figure 2) resulted in a constant yawing moment while that chamber was running. In order to minimize the shutdown transient later, the pilot elected to not retrim the vehicle directionally. The vehicle stabilized in a 1-degree sideslip, and 2 to 5 degrees of aileron and approximately 1 degree of rudder (through the interconnect) were required to maintain zero bank angle. The pilot felt that the vehicle was more sensitive in roll in this situation than during a normal boost with symmetrical thrust.

The pilots felt that the lateral-directional handling qualities of the X-24A during the boost phase were similar to those of the simulator except for the spurious lateral inputs which occurred in flight, but not in the simulator.



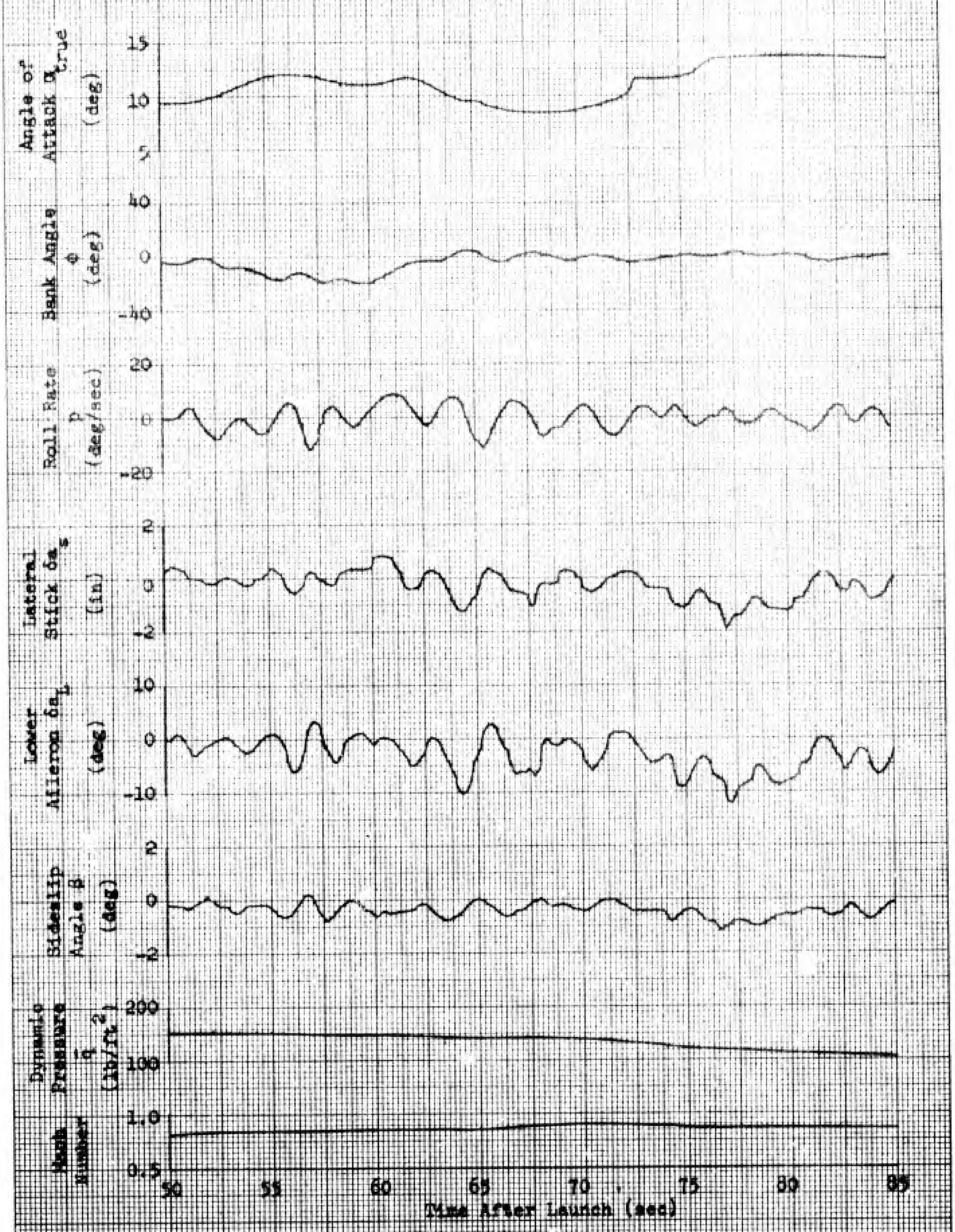


Figure 17. Time History of Lateral Motions During Boost

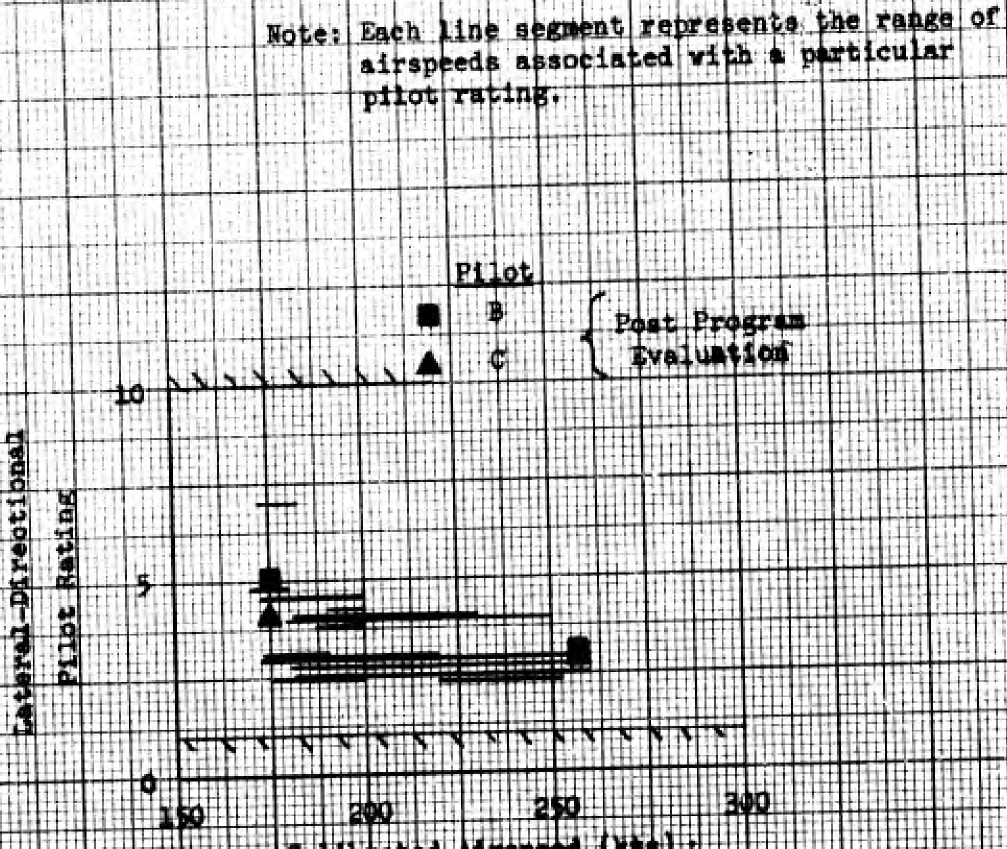


Figure 18. Lateral-Directional Pilot Ratings (Transonic Boost)

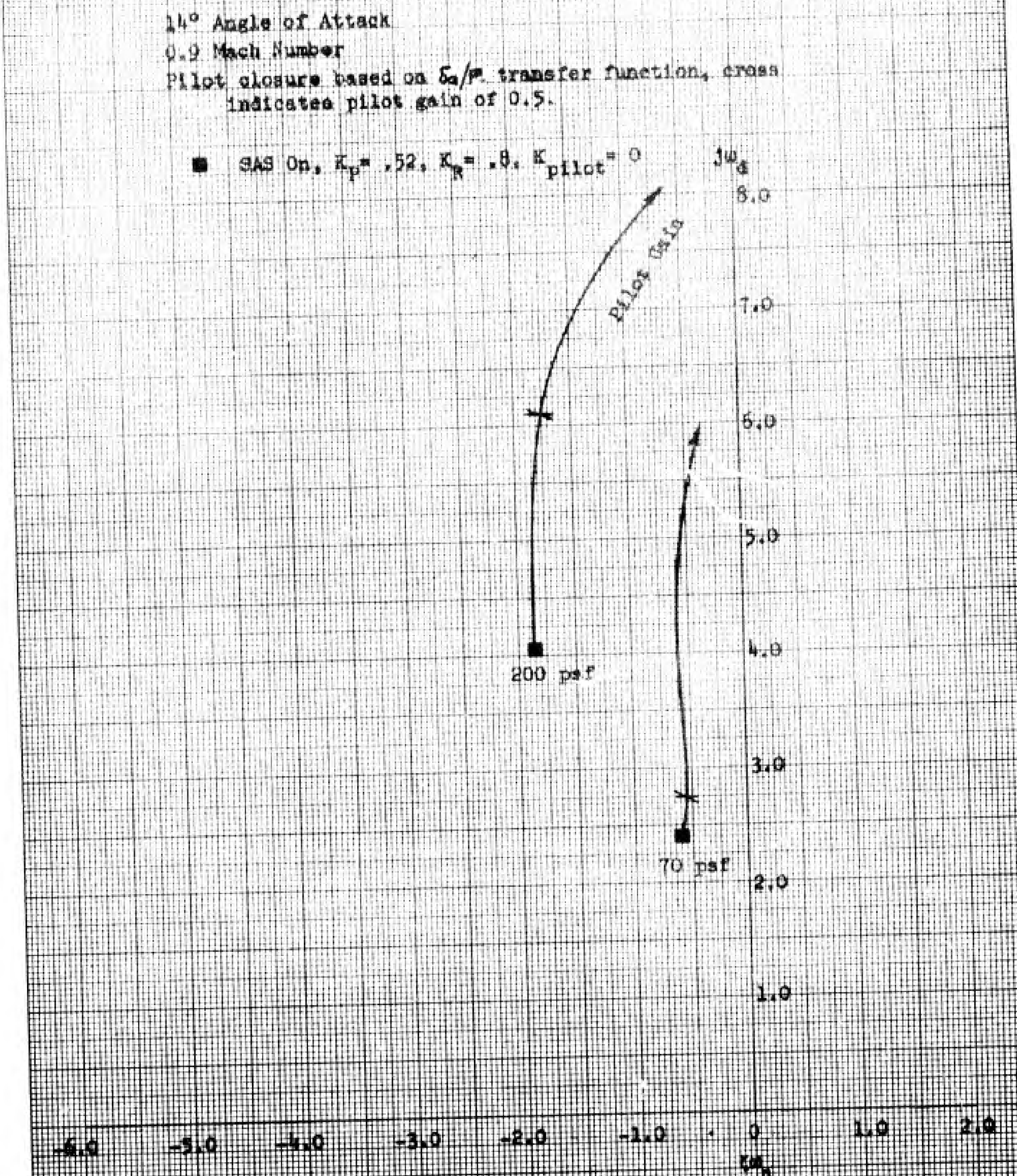


Figure 18. Effect of Dynamic Pressure on Dutch Roll Characteristics and Piloted Response (Transonic Boost Phase)

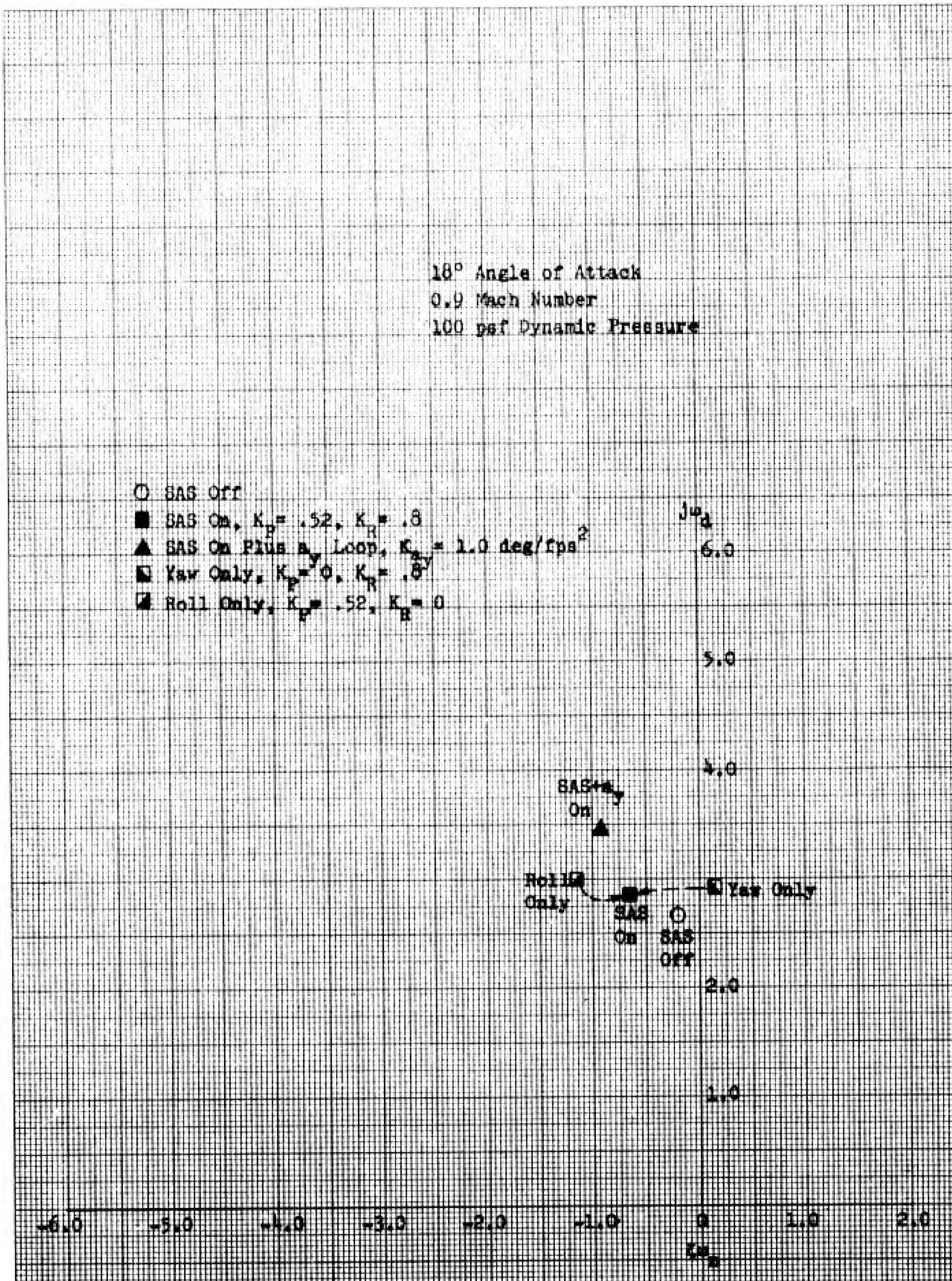


Figure 20. Effect of SAS Gains on Dutch Roll Characteristics (Transonic Boost Phase)

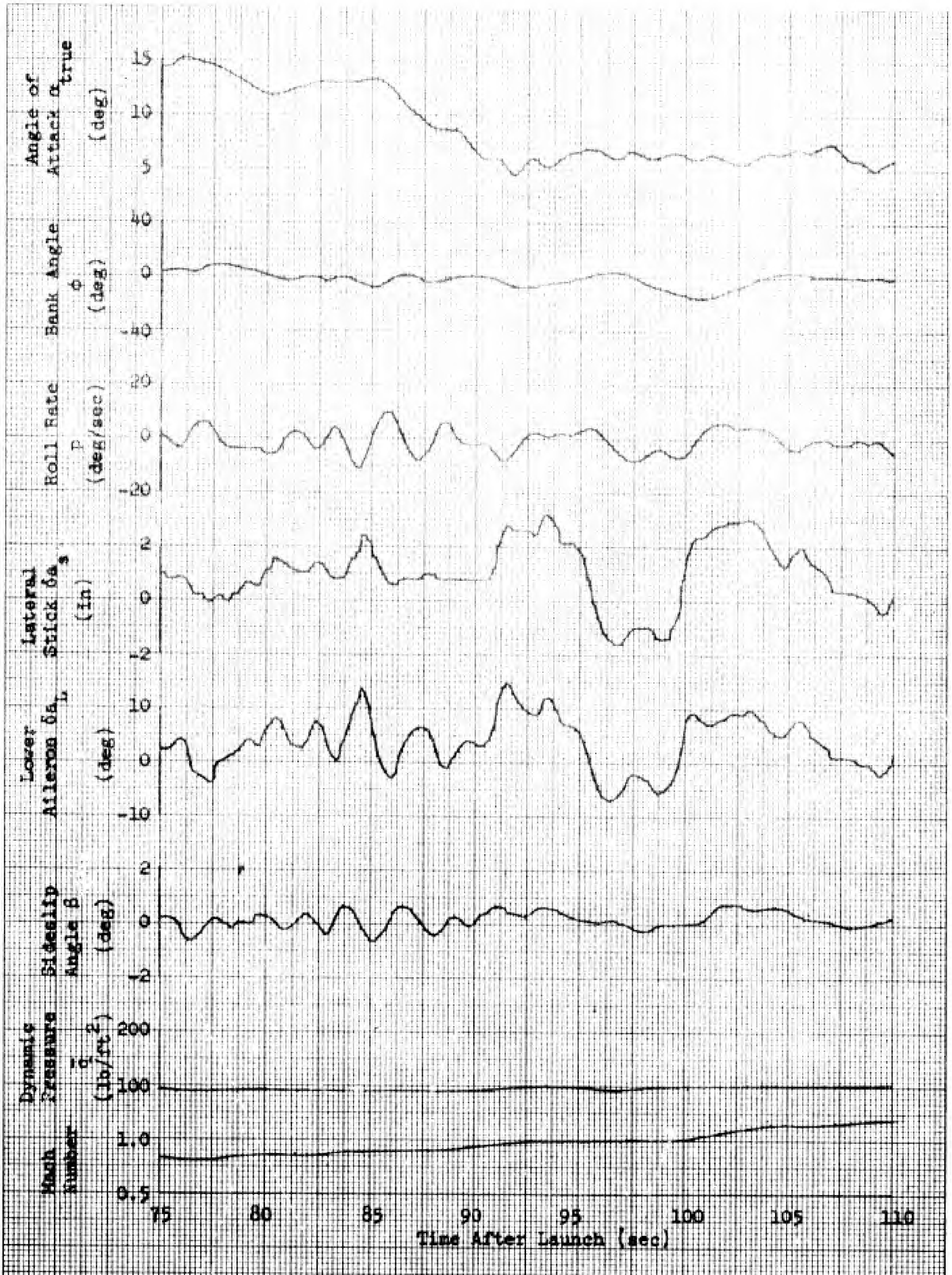


Figure 21. Time History of Low Roll Hover at Pushover

Glide

The transonic handling qualities after rocket engine shutdown were somewhat better than during the boost phase; however, the power-off evaluation flight conditions were usually in the mid angle-of-attack range. Although the flight conditions were similar to those experienced during glide flights, the pilots did not notice any roll disturbances or changes in sensitivity during decelerations in the final vehicle configuration ($-40°\delta U_B$ $0°$ or $2°\delta R_B$). Tuft photos indicated that in this configuration the flow over the tip fins remained spanwise (or separated) during the entire deceleration to 0.5 Mach number until initiation of the configuration change to $-13°\delta U_B$ and $-10°\delta R_B$. The increased flare of upper and lower flaps, compared to that of early glide flights, apparently reduced the severity of the tip fin flow phenomena.

Pilot ratings for the transonic glide phase are shown in figure 22. This figure includes ratings of several different configurations (upper flap, KRA, SAS gains, etc.) and flight conditions (Mach, dynamic pressure, angle of attack) and therefore represents only a broad view of the type of handling qualities which were experienced.

A root locus plot of the Dutch roll pole locations and the effect of pilot gains is shown in figure 23. At high angle of attack (14 degrees), the Dutch roll mode was lightly damped and a pilot gain of 0.5 tended to increase the frequency slightly. At a low angle of attack (6 degrees), the damping was higher; however, the frequency was considerably lower and a pilot gain of 0.5 tended to significantly increase the frequency. This condition is near the roll reversal boundary which was established on the simulator (figure 9).

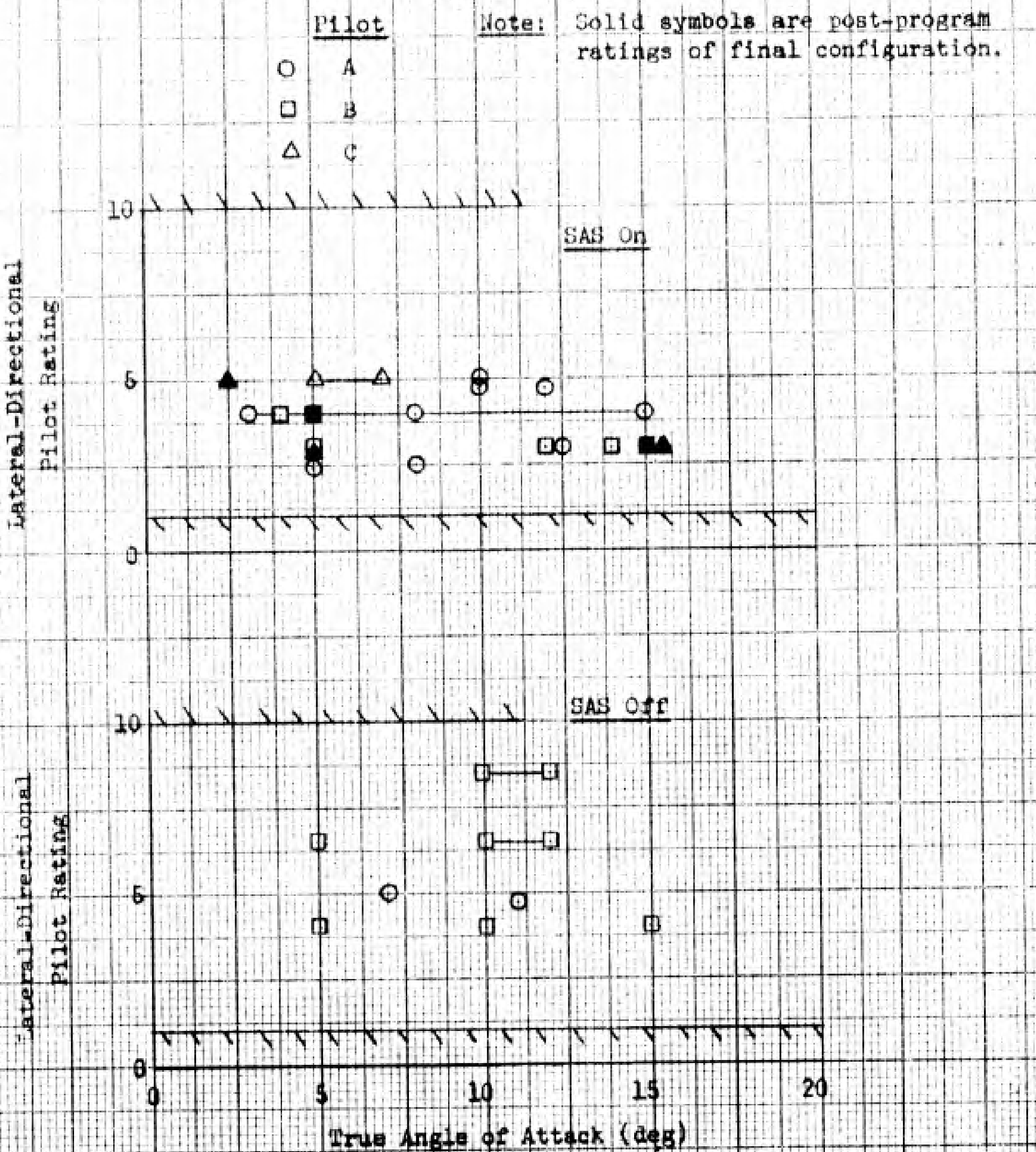


Figure 22. Lateral-Directional Pilot Ratings (Transonic Glide Phase)

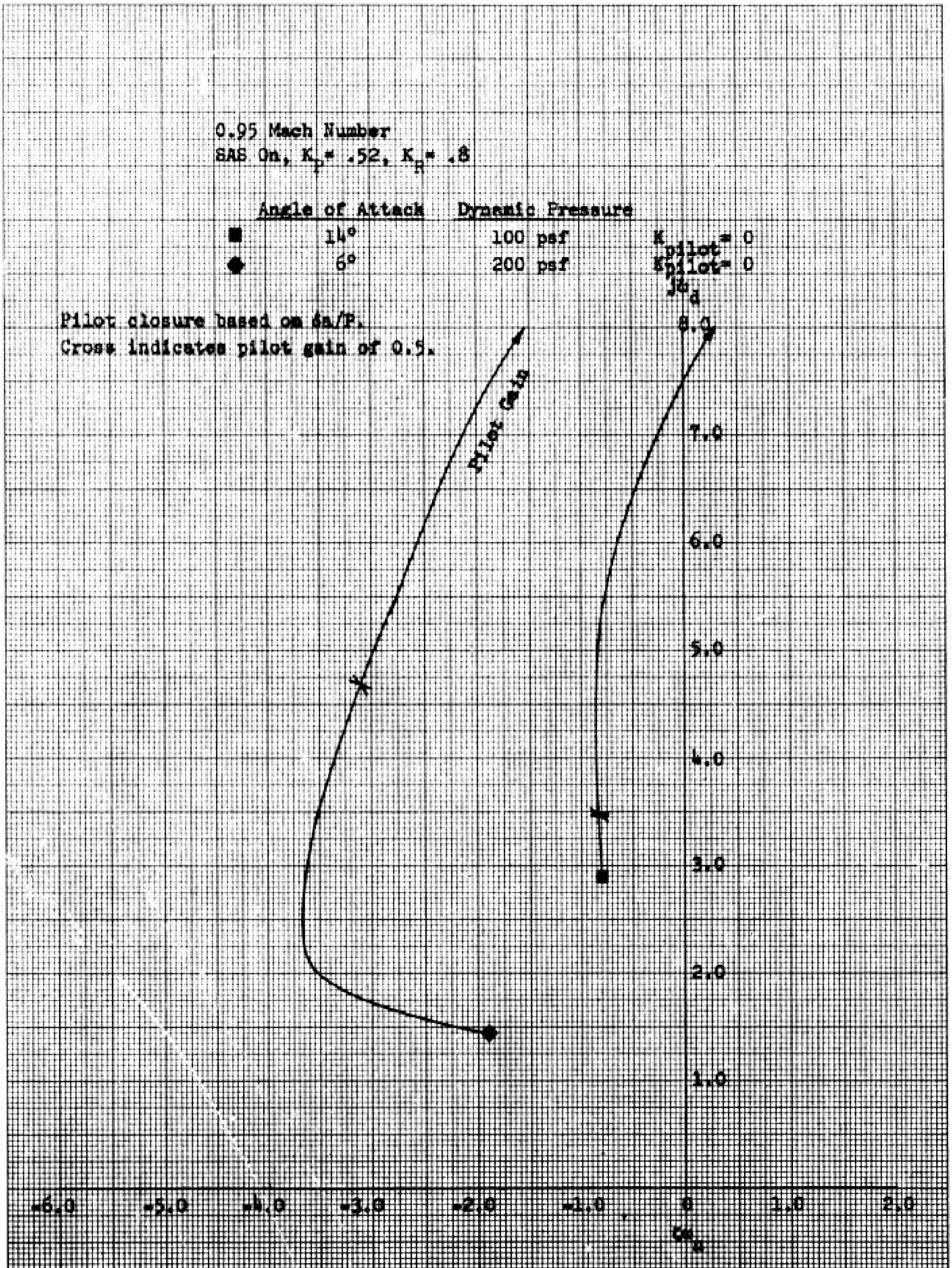


Figure 23. Effect of Angle of Attack on Dutch Roll Characteristics and Piloted Response (Transonic Glide Phase)

SAS-Off

The SAS-off handling qualities of the X-24A were never evaluated during the boost phase.

The roll and yaw dampers were intentionally disengaged several times during the transonic glide phase, usually for the purpose of performing stability derivative maneuvers. On three occasions the pilots were asked to fly and evaluate the SAS-off, lateral-directional handling qualities in the transonic range. The handling qualities were described as overly sensitive with a strong tendency toward a lateral PIO. On one occasion at 0.6 Mach number, 12 to 14 degrees angle of attack, the vehicle was rated 3.0 with only the roll damper disengaged. When the yaw damper was also disengaged, an immediate, divergent, lateral PIO occurred, and the pilot reengaged the yaw damper to stabilize the vehicle as shown in figure 24. The pilot rated the vehicle at 8 to 9 at this time. A few moments later, a second disengagement of the yaw damper was attempted at essentially the same flight condition and, by devoting full attention to the roll control task and using a special pilot technique (applying small, sharp stick inputs with the flat of the hand in one direction only), the pilot was able to control the vehicle and rated it 6.5. During this evaluation the pilot released the stick and observed that the motions damped, thus confirming that the motions were pilot-induced. Notice the correlation between peak roll rates (P) and and lateral stick deflections (δa_s) in figure 24. These characteristics were not totally unexpected. A root locus analysis showed that the pilot could cause the Dutch roll mode to become unstable with fairly low pilot gain (figure 25). Simulator studies had also been performed using the "automatic-pilot-roll-damper" technique discussed in the Pre-Flight Handling Qualities Study section of this report. The configuration and flight conditions were expected to be on the PIO boundary or within the PIO area thus defined. Actual pilot training in the simulator showed that the vehicle would be quite sensitive during this portion of the flight, but did not show as strong a PIO tendency as was predicted by the "automatic-pilot-roll-damper" technique, or actually observed in flight. This difference was felt to be primarily a result of the lack of motion cues in the fixed-base simulator, especially the lateral acceleration at the pilot station produced by high roll accelerations.

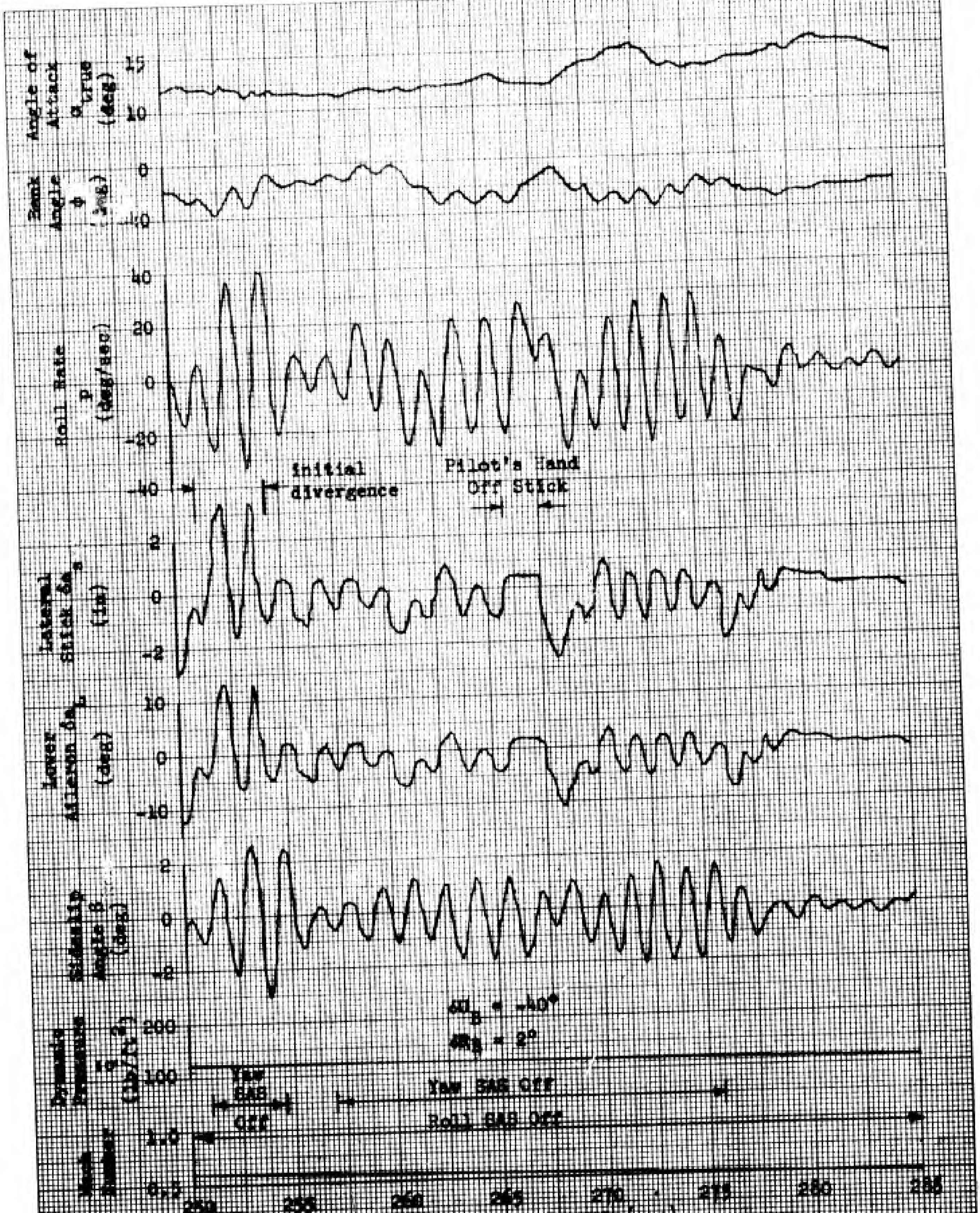


Figure 24. Time History of Lateral Pilot-Induced Oscillation (Roll and Yaw SAS OFF)

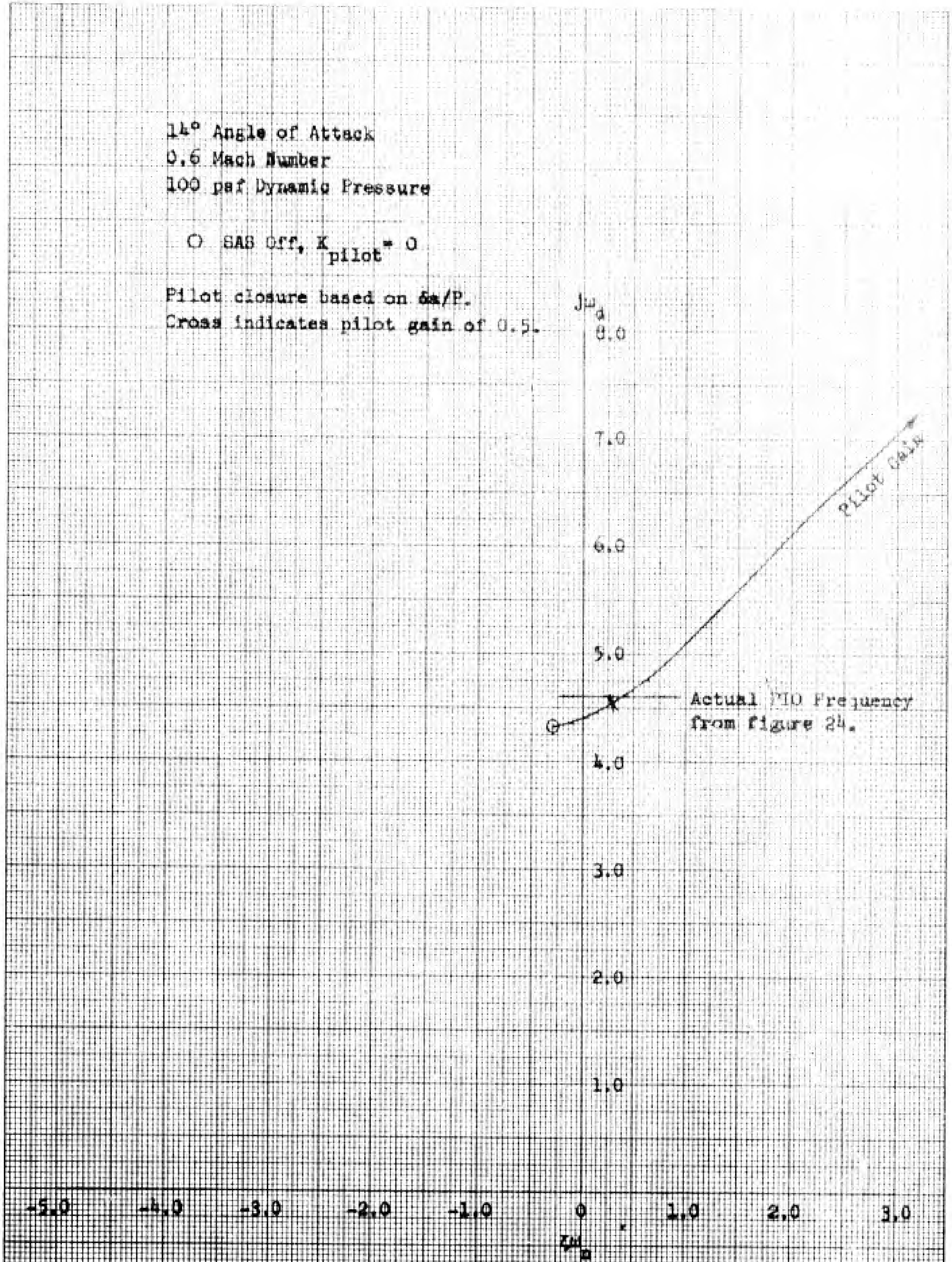


Figure 25. Effect of Pilot Gain on SAS-Off Dutch Roll Characteristics (Transonic Glide Phase)

SUPERSONIC PHASE (Mach Number Greater Than 1.0)

The pilots observed that there was a unique handling quality "sensation" associated with the vehicle's attainment of supersonic flight. The exact nature of this sensation, as to whether it was a change in sound level, change in control sensitivity, trim change, or some combination of these things, was never clearly definable by the pilots, although a small pitch trim change was usually mentioned and was observed in the recorded data. The total flight time at supersonic conditions was only 5.3 minutes, so the pilots' evaluations were quite brief.

Configurations Flown

The configurations and supersonic flight envelope flown during the test program are shown in figures 12 and 13. Only one upper flap setting (-40 degrees) and two rudder bias settings (zero and 2 degrees) were flown at supersonic speeds. The range of supersonic angles of attack flown was also rather small, due to the requirement for low angle of attack (low drag) during the boost phase and the rapid deceleration which followed engine shutdown. Since supersonic test time was at a premium, the pilot evaluations and ratings were made while performing closely spaced test maneuvers under highly transient conditions and must be considered s only broad appraisals of the handling qualities.

Longitudinal Handling

As predicted, the X-24A became quite stable in the longitudinal axis from 1.0 to 1.6 Mach number between 5 and 12 degrees angle of attack. Large stick and lower flap deflections were required to change angle of attack as compared with the subsonic characteristics. As a result, the longitudinal trim rates were slower than desirable. Damping was adequate and the pilots felt that they had good control of the vehicle in pitch, and assigned it a pilot rating of 2.0. Supersonic power-on and power-off trim curves are shown in figure 26. Note the absence of the power-on trim increment which was observed in transonic flight. The somewhat abrupt disappearance of this power-trim increment as the vehicle accelerated past Mach 1 is believed to be a part of the supersonic "sensation" described by the pilots. It was difficult for the pilots to confirm this since they were usually not in stabilized flight but were still reducing angle of attack in the pushover maneuver when the vehicle attained Mach 1. The transonic trim change due to Mach effects alone is shown in figure 27. There was no abrupt trim change associated with the power-off deceleration through Mach 1.0 in the mid angle-of-attack range which was normally flown (8 to 10 degrees).

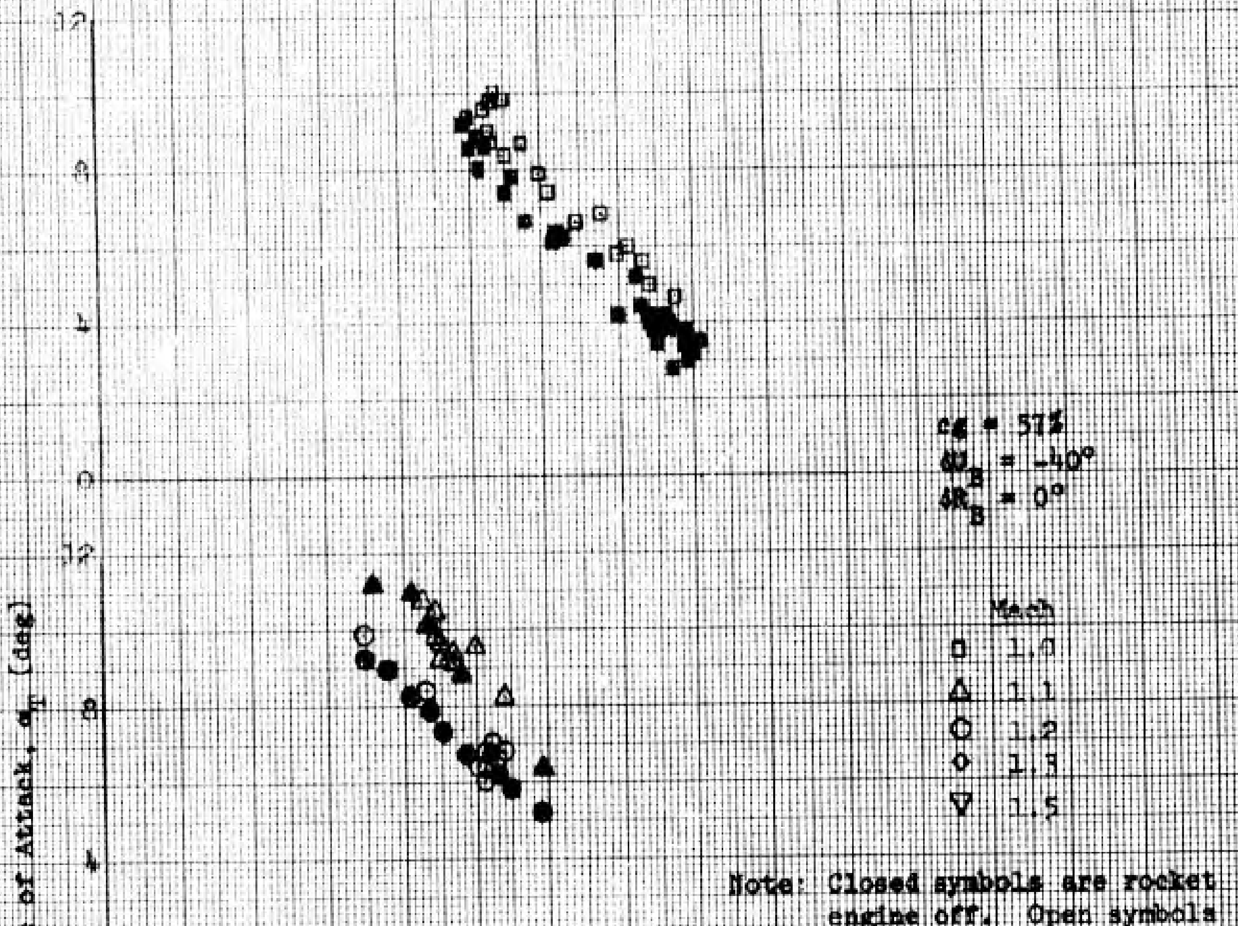


Figure 26. Supersonic Longitudinal Trim Curves

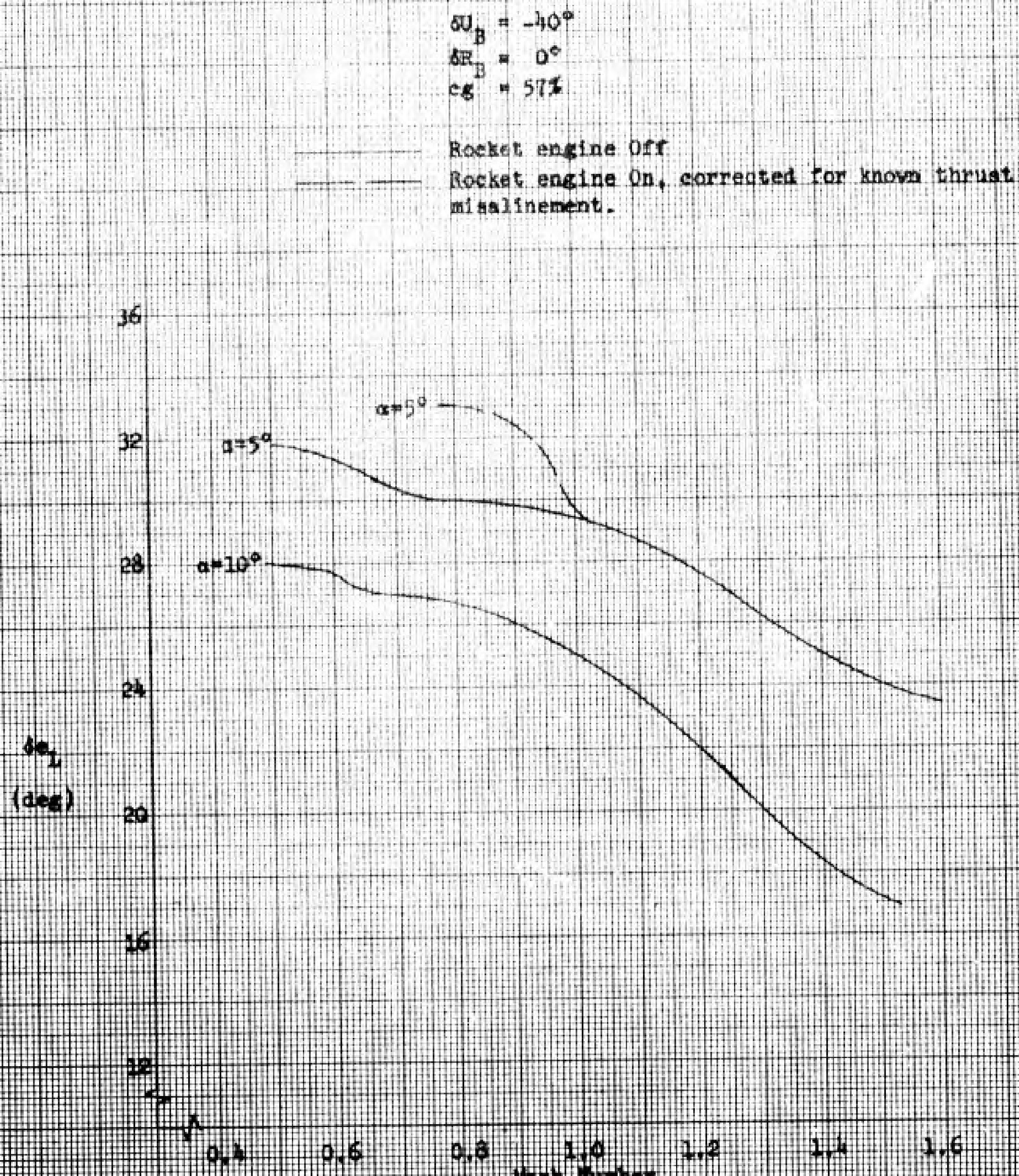


Figure 27. Effect of Mach Number on Longitudinal Trim

Lateral-Directional Handling

The supersonic lateral-directional handling qualities were generally rated at 2.0 to 2.5. The vehicle was described as having a more "solid" feel than at transonic speeds. This was evident in the recorded data as a smoothing out of the sideslip trace. The lateral axis was quite sensitive to rudder movement with rather large roll rates produced by the rudder doublet maneuvers. Lateral control power was low, but adequate for normal maneuvering. The closed loop characteristics of the final configuration as they varied with pilot gain are shown in a root locus presentation in figure 28. The modes are seen to be stable and well-damped, supporting the pilot comments.

At 1.3 Mach number above 10 degrees angle of attack, the static directional stability, C_{n_β}, was found to be significantly reduced while the rocket engine was running (reference 5). This was assumed to be another aerodynamic effect produced by the rocket engine exhaust plume. At the time the test maneuvers were performed at this condition, the pilot was not able to identify any significant handling qualities deficiencies, although he did indicate that the vehicle "felt sluggish" and rated it 2.5 and 3.0.

A root locus analysis using the negative value of C_{n_β} obtained from one rudder doublet is shown in figure 29. Notice that in spite of the negative C_{n_β} the characteristics were not significantly different from the characteristics with predicted C_{n_β} except for the lower Dutch roll frequency. The time in this environment was obviously too short for the pilot to detect this difference. Following the test maneuver the vehicle stabilized with a left sideslip of approximately 0.8 degrees and the pilot used approximately 14 degrees of left aileron deflection (which in turn produced about 3.5 degrees of left rudder from KRA) to maintain a zero bank angle. At engine shutdown the normal level of C_{n_β} was restored and the sideslip and controls returned to zero (reference 5). Although the handling qualities did not appear to be grossly affected by this loss in directional stability, the trends in the data and simulator studies showed that catastrophic results could be expected if the stability level were only slightly lower than experienced in flight. Subsequent to this flight, the supersonic rudder bias setting was changed from zero to +2 degrees in an effort to regain the desired directional stability level with the rocket engine on. Flights in the +2 degrees δR_B configuration did not indicate any significant change in handling qualities and insufficient data maneuvers were performed during the remaining flights of the program to fully evaluate the effects on power-on C_{n_β} in the 1.3 Mach number, 13-degree angle-of-attack region.

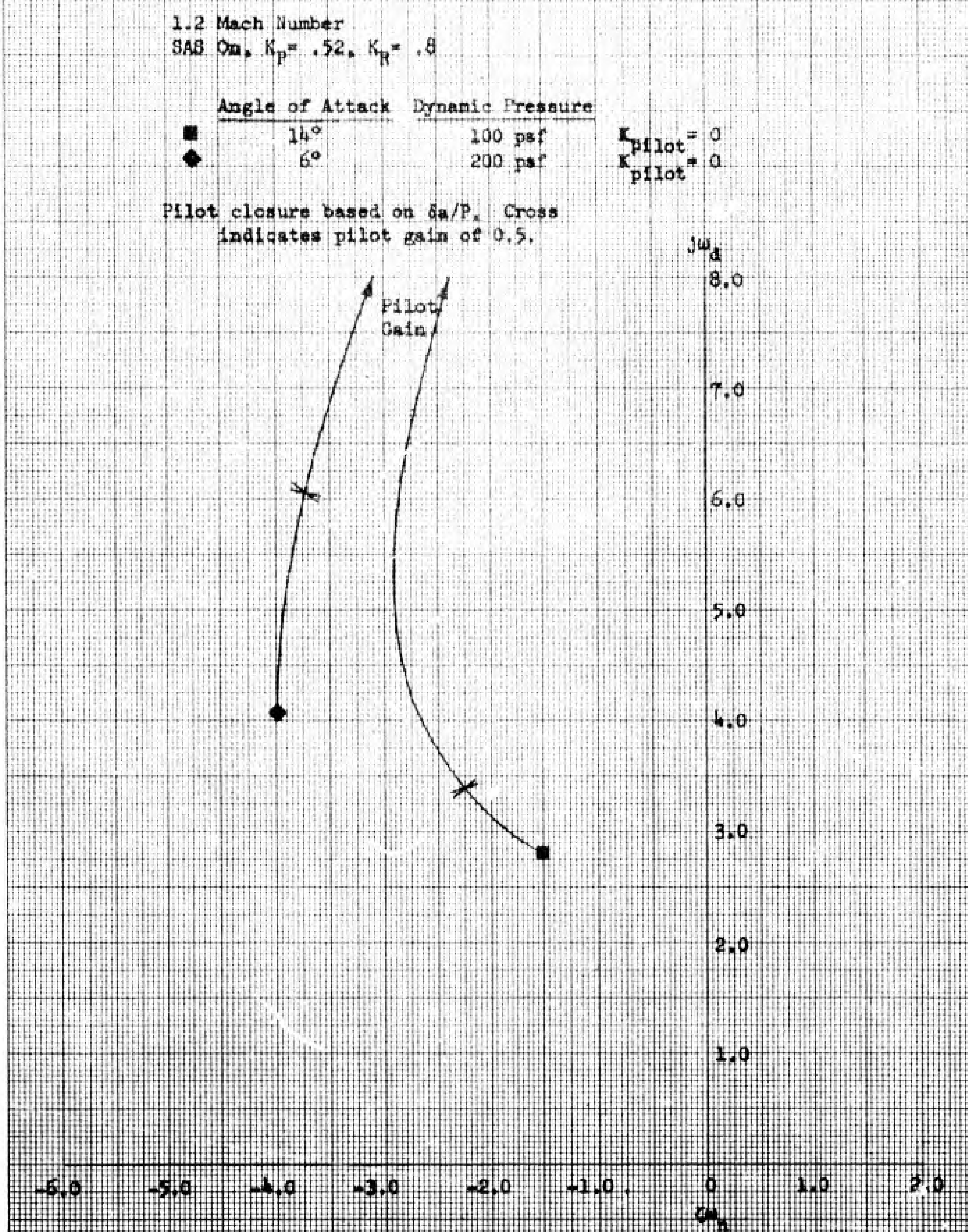


Figure 28. Effect of Pilot Gain on Dutch Roll Characteristics (Supersonic Phase)

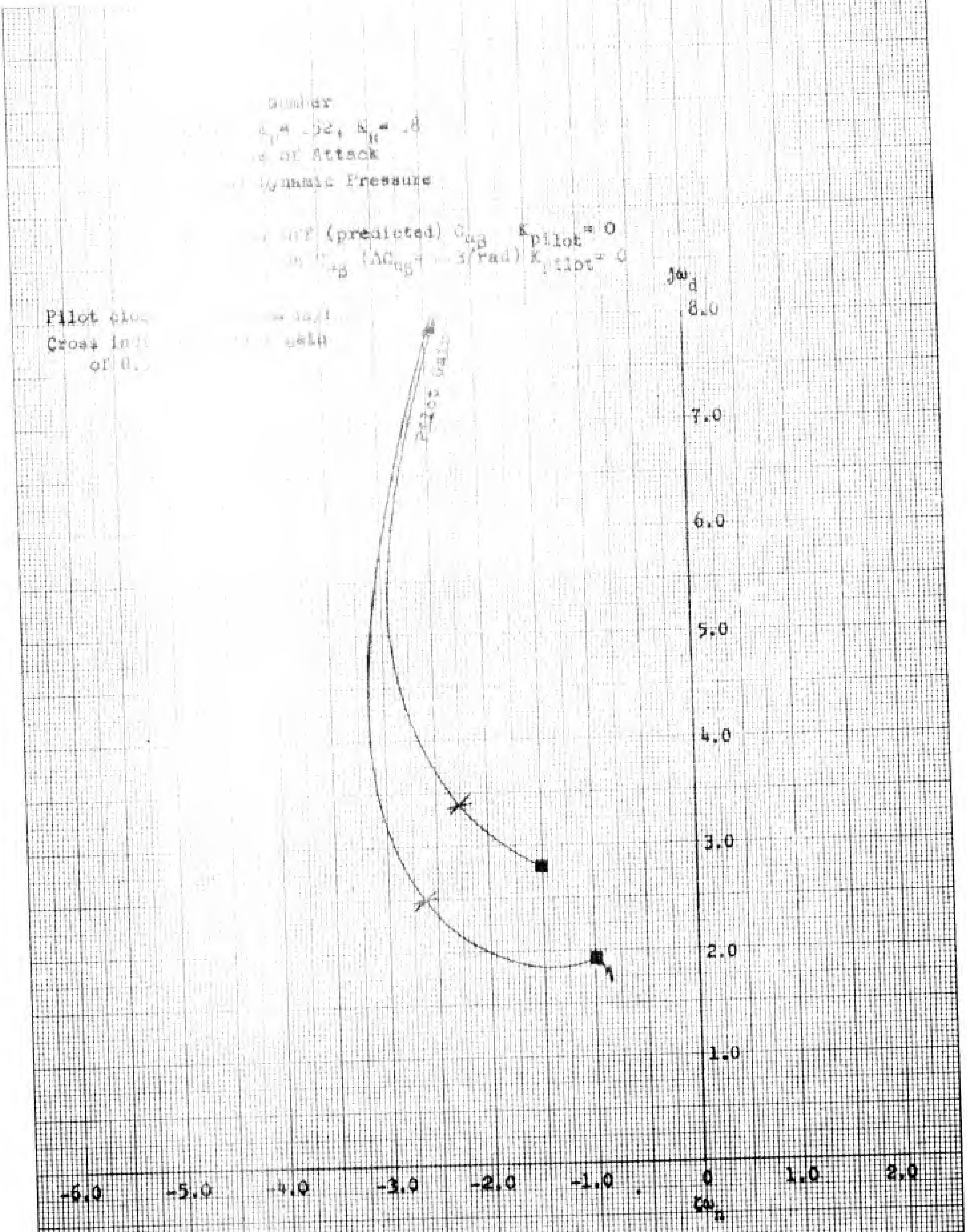


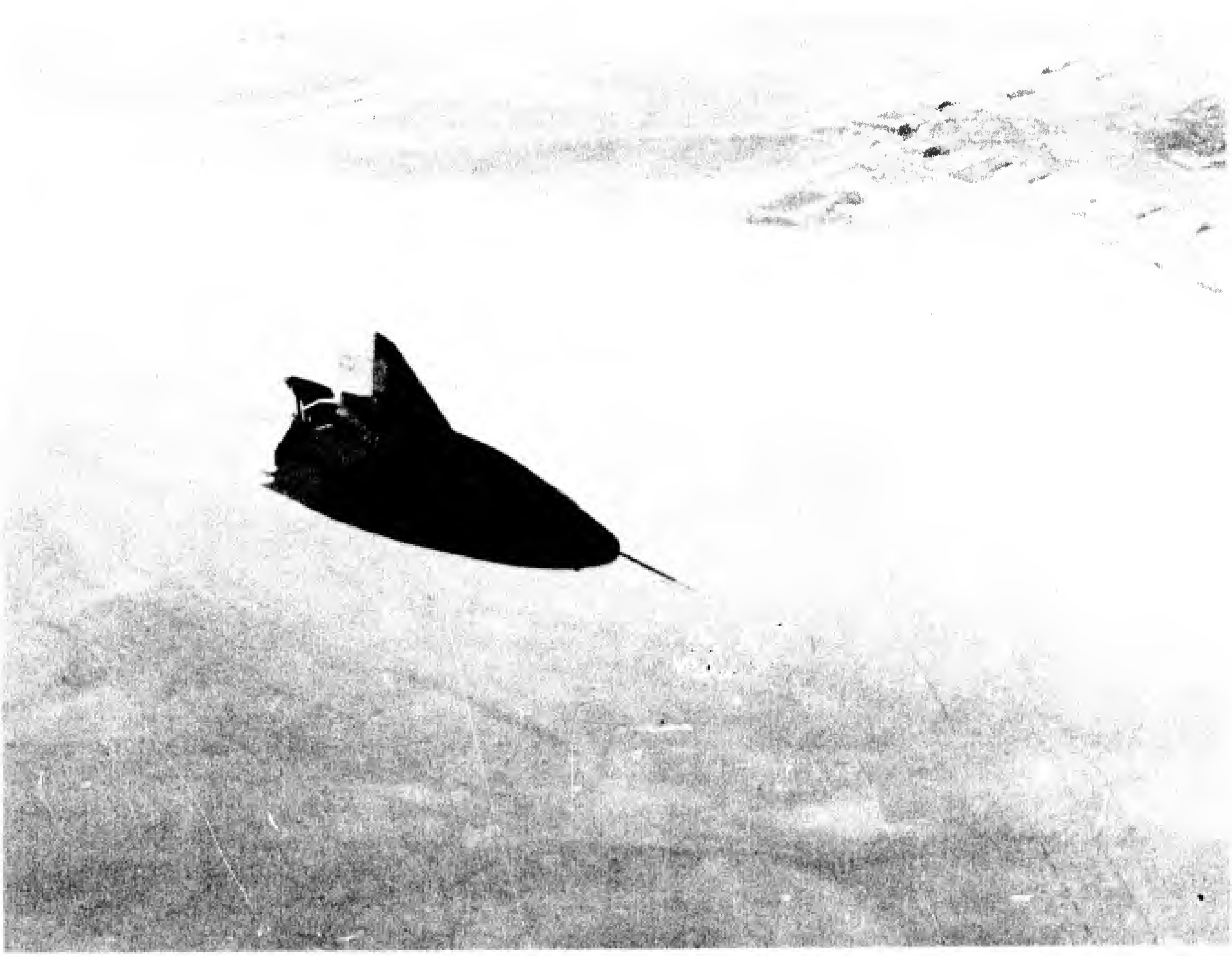
Figure 29. Effect of Negative C_{n_β} on Lateral-Directional Characteristics (Supersonic Phase)

APPROACH PHASE (Mach 0.6 to Landing Flare)

The aerodynamics in the approach phase were characterized by smooth and generally chordwise flow over the entire vehicle, including the inboard tip fin surfaces. The handling qualities of the X-24A during the approach phase in the final configuration were described as excellent by the pilots and were compared favorably with those of modern jet fighters. Lateral-directional handling qualities and riding qualities deficiencies were observed on early glide flights, but were dispelled through a combination of control system modifications and pilot experience.

Configurations Flown

The approach configurations and flight conditions experienced during the test program are summarized in figure 30. A detailed discussion of the approaches and landings performed during the X-24A program can be found in reference 6. Since the approach and landing technique and piloting task were essentially the same for each flight, a fairly good sampling of pilot comments and ratings was obtained. Comparative evaluations were accomplished, especially with different upper flap settings, SAS gains, and KRA settings.



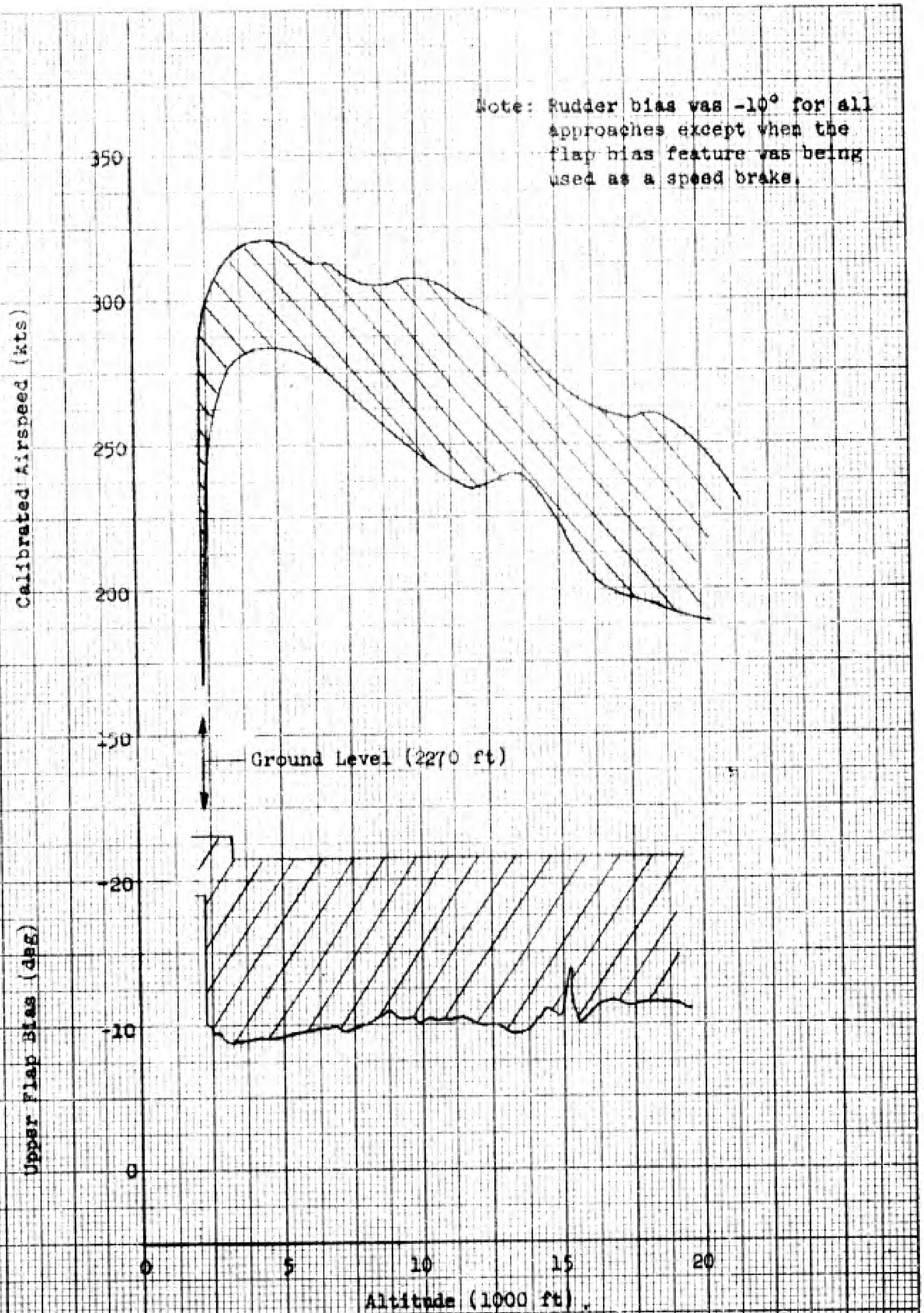


Figure 30. X-24A Landing Approach Conditions Flown

Longitudinal Handling

The longitudinal handling qualities of the X-24A during the approach phase were considered good to excellent and were consistently rated between 2 and 3 even in light turbulence. The longitudinal trim curves for all approach configurations flown were stable and linear over the normal angle-of-attack range (figure 31) and short period damping was excellent. The pilots felt that the vehicle flew very much like the simulator in the pitch axis.

Prior to Flight 9 the configuration change from the transonic configuration to the approach and landing configuration was performed by independently and sequentially activating the rudder bias and upper flap bias systems. The longitudinal trim change, due to rudder bias movement from zero to -10 degrees at constant angle of attack, was approximately 10 degrees of lower flap or 4 inches of stick movement occurring over a 3.3-second period (figure 32). Closing the upper flaps from -30 to -13 degrees resulted in a lower flap change of 24.5 degrees, but only 3.8 inches of longitudinal stick movement, due to the compensation from the lower flap bias linkage (figure 33) (reference 4). Time for closure of the upper flaps was approximately 6 seconds. Both of these trim changes were easily controlled by the pilot by maintaining essentially constant attitude while the surfaces were moving. The pilot rating in pitch for independent upper flap and rudder bias configuration changes was 3.0.

Since the two trim changes were opposite in sign, a control system modification was made between flights 8 and 9 which slaved the rudder bias to the upper flap bias between -13 and -35 degrees δU_B in such a manner as to minimize the total trim change at the stick during the configuration change. The longitudinal stick movement was reduced to 2.0 inches, and the pilot rating in pitch during the configuration change was improved to 2.5. The combined rudder and flap configuration change was also simpler and quicker to perform, thus providing a significant improvement from the operational viewpoint, since it minimized pilot workload. The combined rudder and upper flap bias configuration change was used for the remainder of the test program. A typical history is shown in figure 34.

The pitch trim change associated with the configuration change was consistently found to be easier in flight than in the simulator. This same trend has been observed on the other lifting body vehicles and is felt to be the result of motion cues and the visual attitude reference afforded by the horizon in flight.

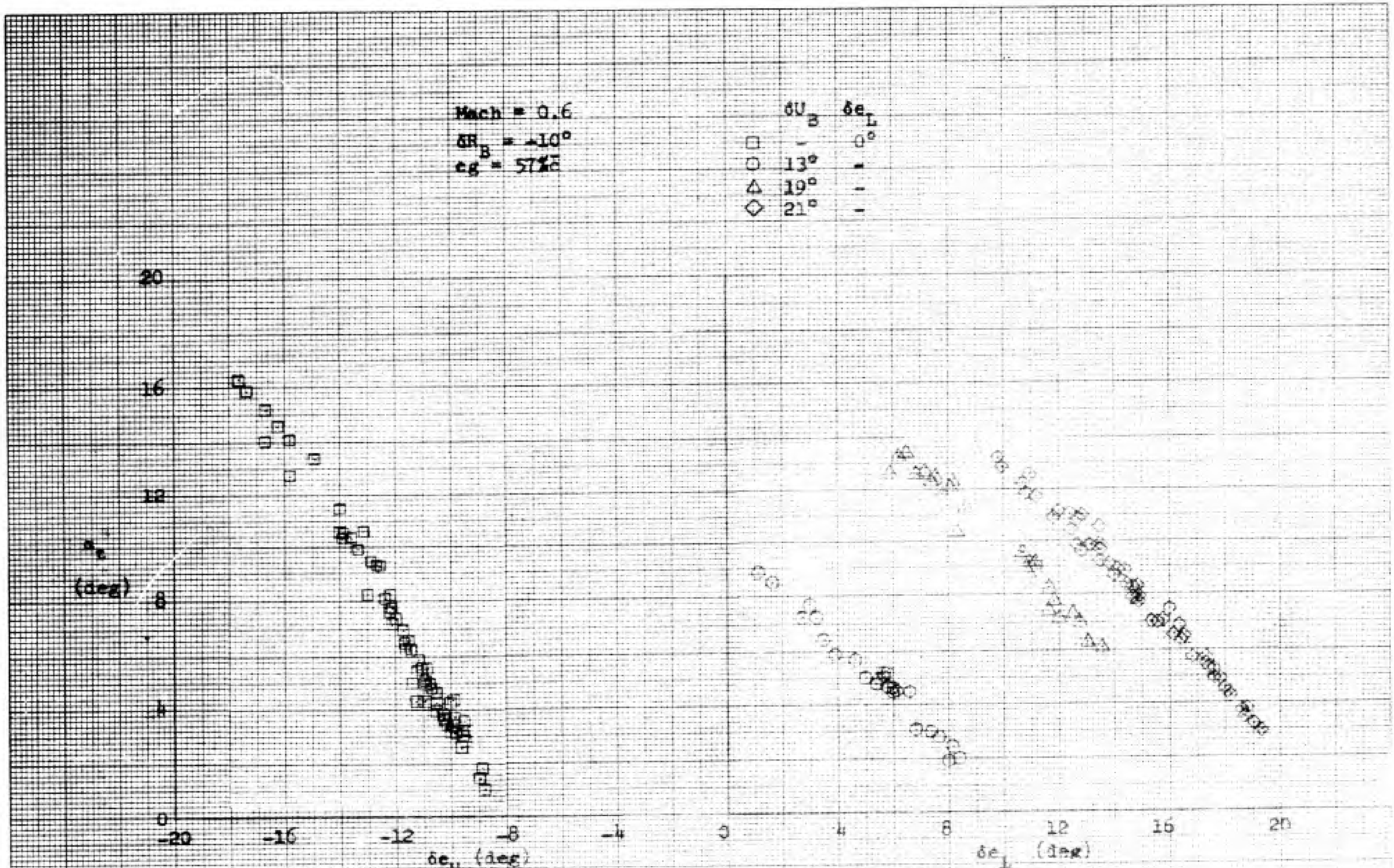


Figure 31. Longitudinal Trim Curves (Approach Phase)

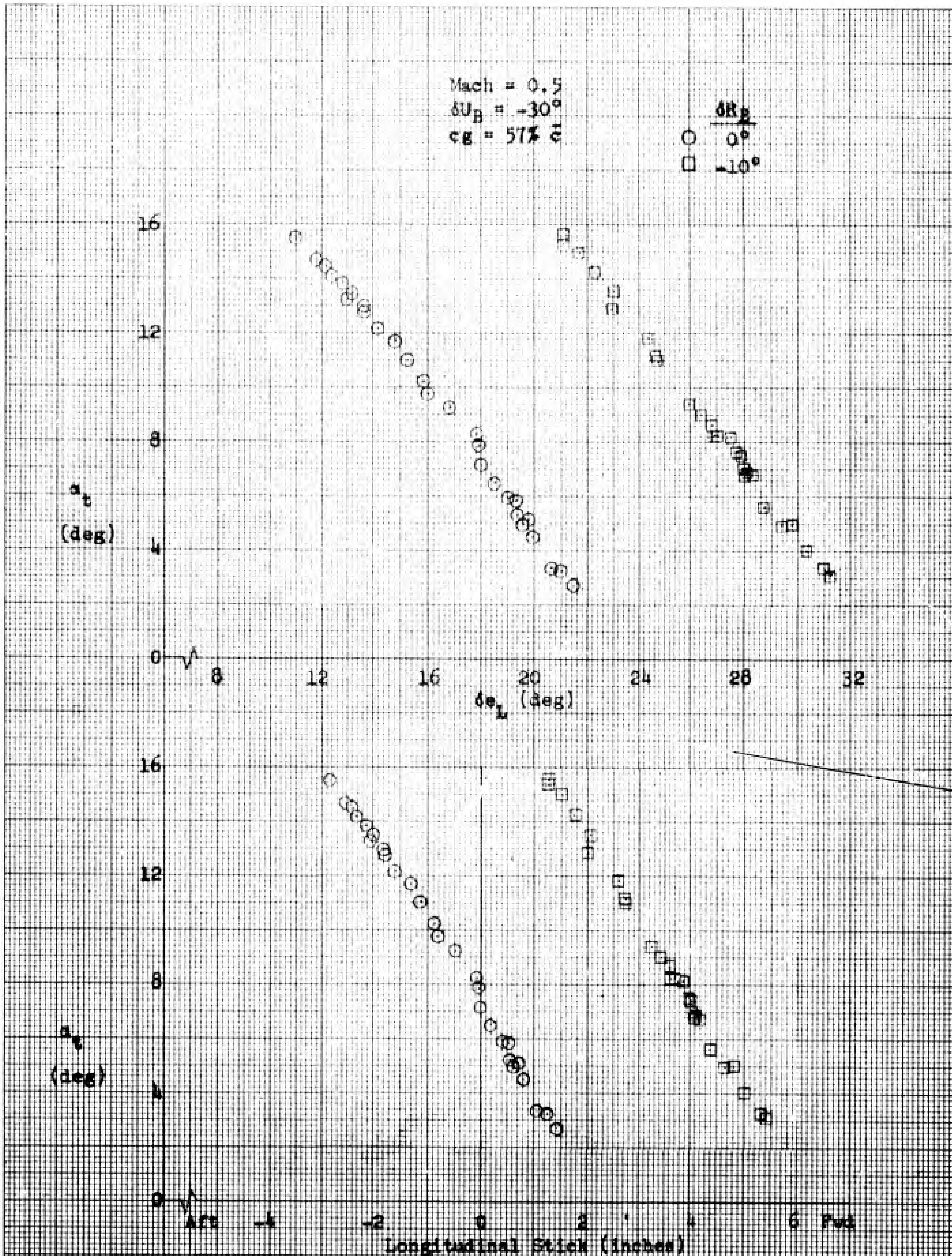


Figure 32. Longitudinal Trim Change Due to Rudder Bias

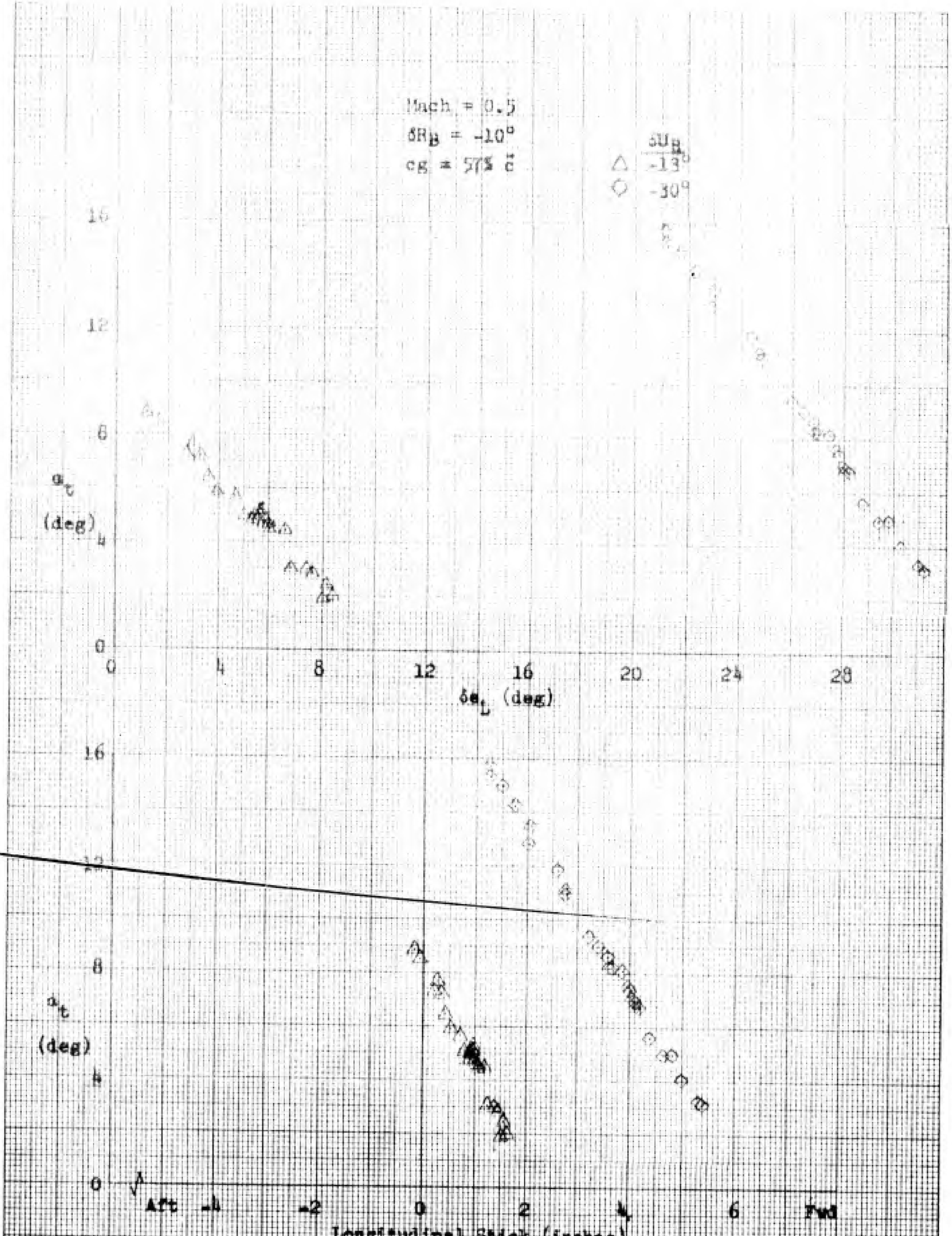


Figure 33. Longitudinal Trim Change Due to Upper Flap Bias

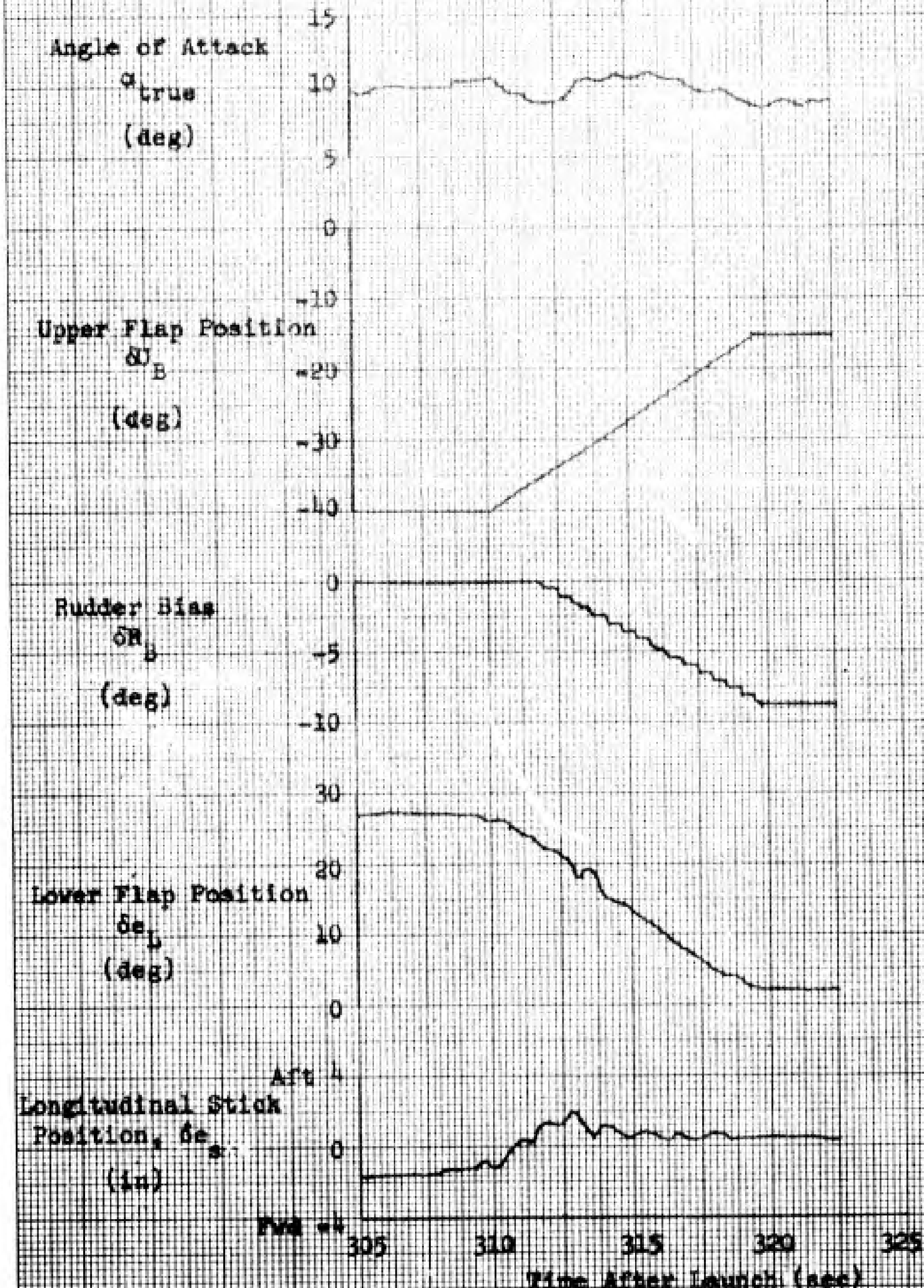


Figure 34. Time History of Configuration Change with SAS On

Lateral-Directional Handling

Expected Characteristics

The lateral-directional handling qualities during the high energy approach of the X-24A were of major concern even before the first glide flight. Simulator studies showed that the low roll effectiveness of the lower flaps ($C_{\ell_{\delta_a}}$) and the high dihedral effect (C_{ℓ_β}) resulted in lateral characteristics which were highly susceptible to any yaw-producing control inputs or yaw disturbances. In particular, changes in the yawing moment due to differential lower flap deflection ($C_{n_{\delta_a}}$) and the yawing moment produced by the rudder through the interconnect (KRA x $C_{n_{\delta_r}}$) resulted in significant changes to lateral controllability and sensitivity. Changes which produced excessive proverse yaw (plus $C_{n_{\delta_a}}$ or high KRA) created a lateral PIO problem, whereas excessive adverse yaw (negative $C_{n_{\delta_a}}$ and low or zero KRA) produced roll reversal. Wind tunnel error analyses showed that fairly large errors (of the order of ± 0.01) might be expected in the wind tunnel predictions of $C_{n_{\delta_a}}$. The effect of $C_{n_{\delta_a}}$ variation and errors in $C_{n_{\delta_a}}$ are shown in figures 6 and 7 and are discussed in the Preflight Handling Qualities section of this report.

Early Flight Experience

During the first X-24A flight, a malfunction in the KRA system occurred which locked the KRA at 0.096 (35-percent indicated) for the approach and landing. As the pilot was accelerating on final approach at 3 degrees angle of attack, he detected uncomfortable lateral motions of the vehicle and elected to reduce airspeed and use the landing rockets during the flare and landing. Although no test maneuvers were performed, there were preliminary indications in the data that $C_{n_{\delta_a}}$ might be proverse rather than adverse as predicted. Analysis of vehicle motions during the approach showed that the pilot's lateral stick activity was exactly opposed to roll rate, and the motions, although small, were judged to be pilot-induced, resulting from the KRA malfunction and consequent high value of KRA. Note that the actual first-flight approach conditions were within the PIO region indicated by figure 6. The first-flight questionnaire was used to evaluate the simulator handling qualities before the first flight. The same questionnaire was used to evaluate the actual first-flight handling qualities. Both sets of pilot ratings are shown in appendix III.

To prevent lower flap surface rate limiting after gear deployment the landing approach on the second flight was flown with lower yaw gain and higher roll gain (see Landing Phase section). Although the KRA system performed properly on this flight, the pilot again detected uncomfortable lateral motions, and momentary rate-limiting of the lower flaps occurred before and during the flare (figure 35). The pilot again elected to decelerate and use the landing rockets during flare. He assigned a pilot rating of 6 to 7 for the lateral-directional handling qualities during the approach on this flight.

A concentrated analysis of the approach handling qualities problem followed the second flight, and several potential causes and contributing factors were identified. Several changes were made to the control system before the third flight. A combination of pilot learning and control system refinements continued on subsequent glide flights, such that after Flight 7, the approach handling qualities were rated between 2 and 3 by the pilots. Details of control system changes are discussed in reference 4.

Each of the factors which were felt to have influenced the approach handling qualities on early flights are discussed in the following paragraphs.

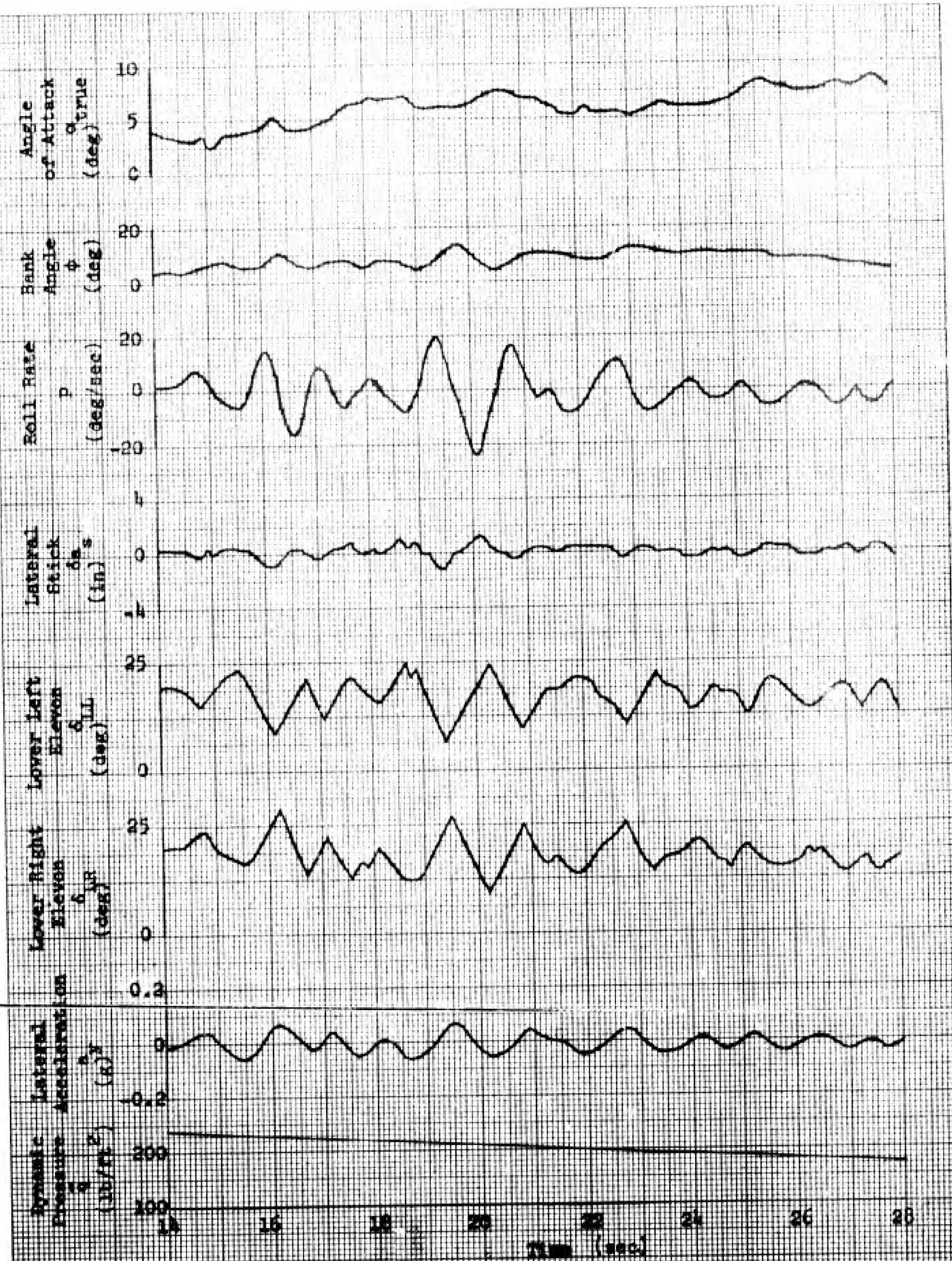


Figure 55. Time History of Control Surface Rate Limiting (Approach Phase, Flight 2)

Proverse Yaw Due to Aileron

The effects of roll and yaw SAS gains on the location of the Dutch roll pole for the first flight approach conditions are shown in figures 36 and 37 (predicted and actual). Starting from the SAS-off condition on figure 36 (predicted Cn_{δ_a}) it can be seen that either the yaw or the roll damper provided a significant increase in damping. The combination of both yaw and roll SAS on provided an increase in frequency and thus an improvement in the time to damp, since the damping ratio remained essentially unchanged. Using the flight test proverse value of Cn_{δ_a} (figure 37), and again starting from the SAS-off condition, it can be seen that the roll damper alone decreased the Dutch roll damping while the yaw damper again increased damping, with the best combination being a low roll gain and high yaw gain. Notice that this is opposite to the SAS gain relationship desired for the boost phase as shown in figure 20.

On flights subsequent to Flight 2, the yaw gains were increased and roll gains reduced for the approaches. Pilot ratings are plotted versus the ratio of yaw gain to roll gain in figure 38. The final selected gains were switch position 2 in roll (0.34 deg/deg/sec) and position 7 in yaw (0.80 deg/deg/sec), which resulted in the Dutch roll characteristics shown in figure 39. The amount of improvement provided by various changes could not be separated however, the establishment of the proper ratio of roll to yaw SAS gains was probably the most helpful in improving the overall approach characteristics.

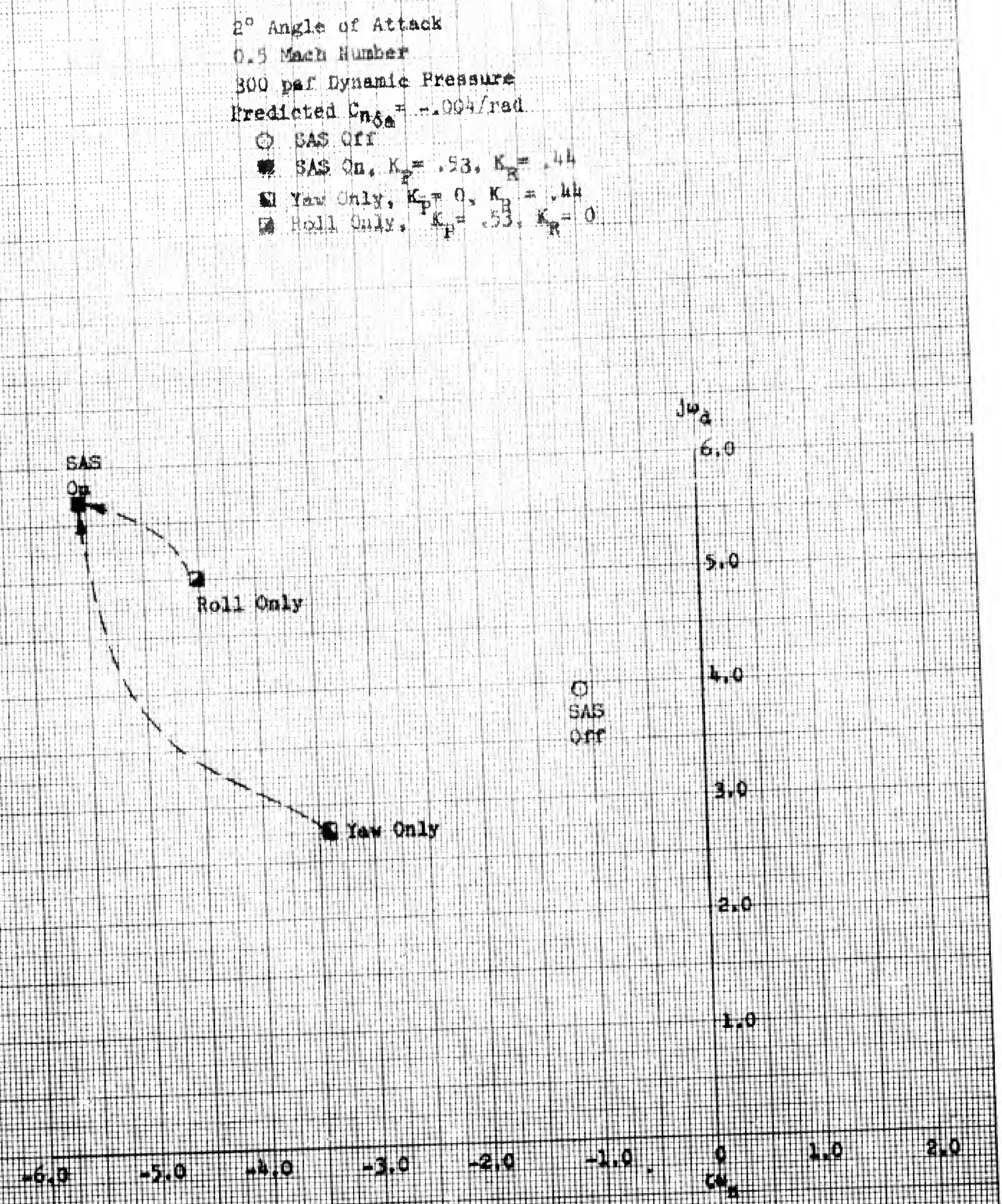


Figure 36. Predicted First-Flight Dutch Roll Characteristics (Approach Phase)

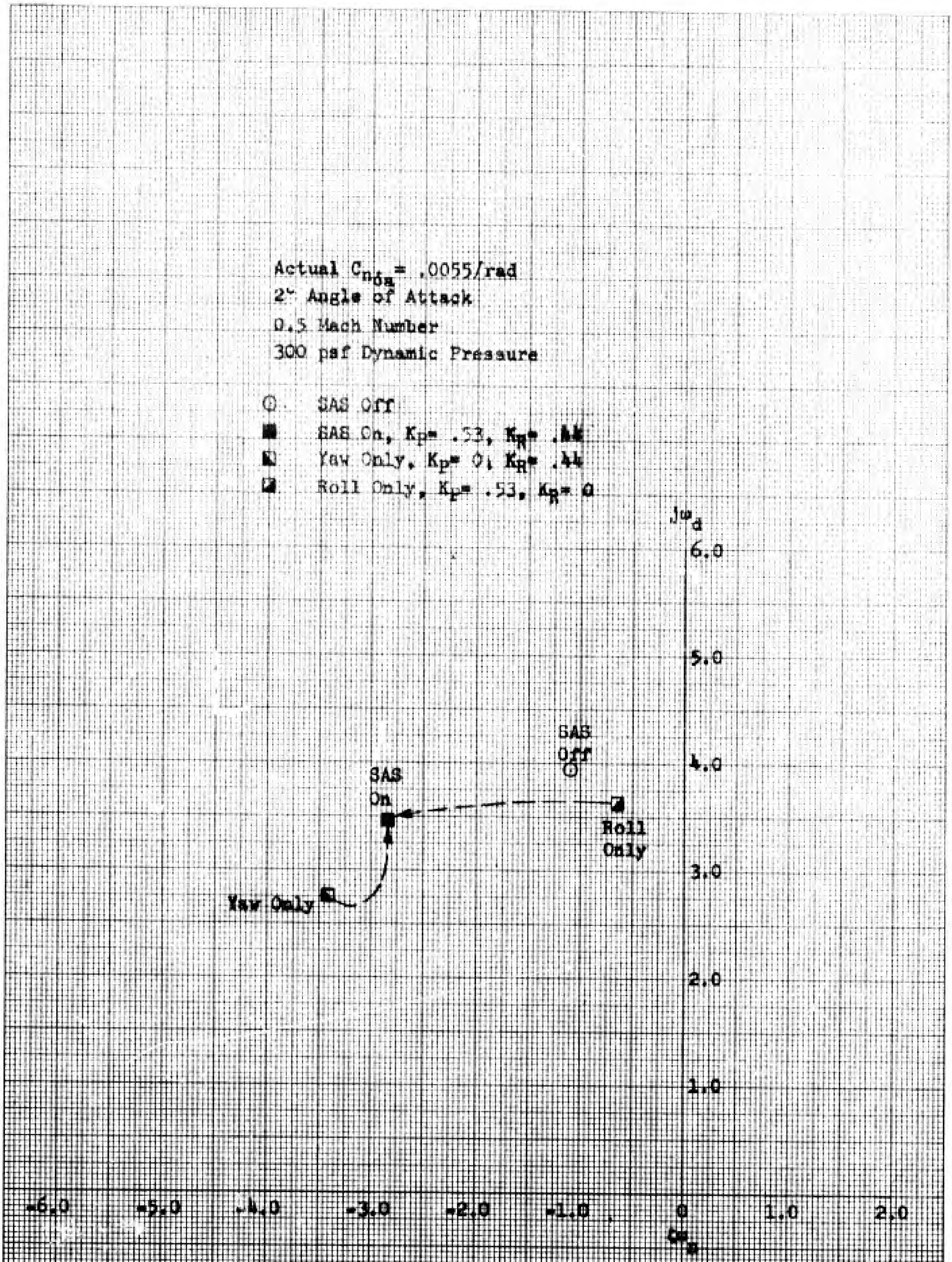


Figure 37. Actual First-Flight Dutch Roll Characteristics (Approach Phase)

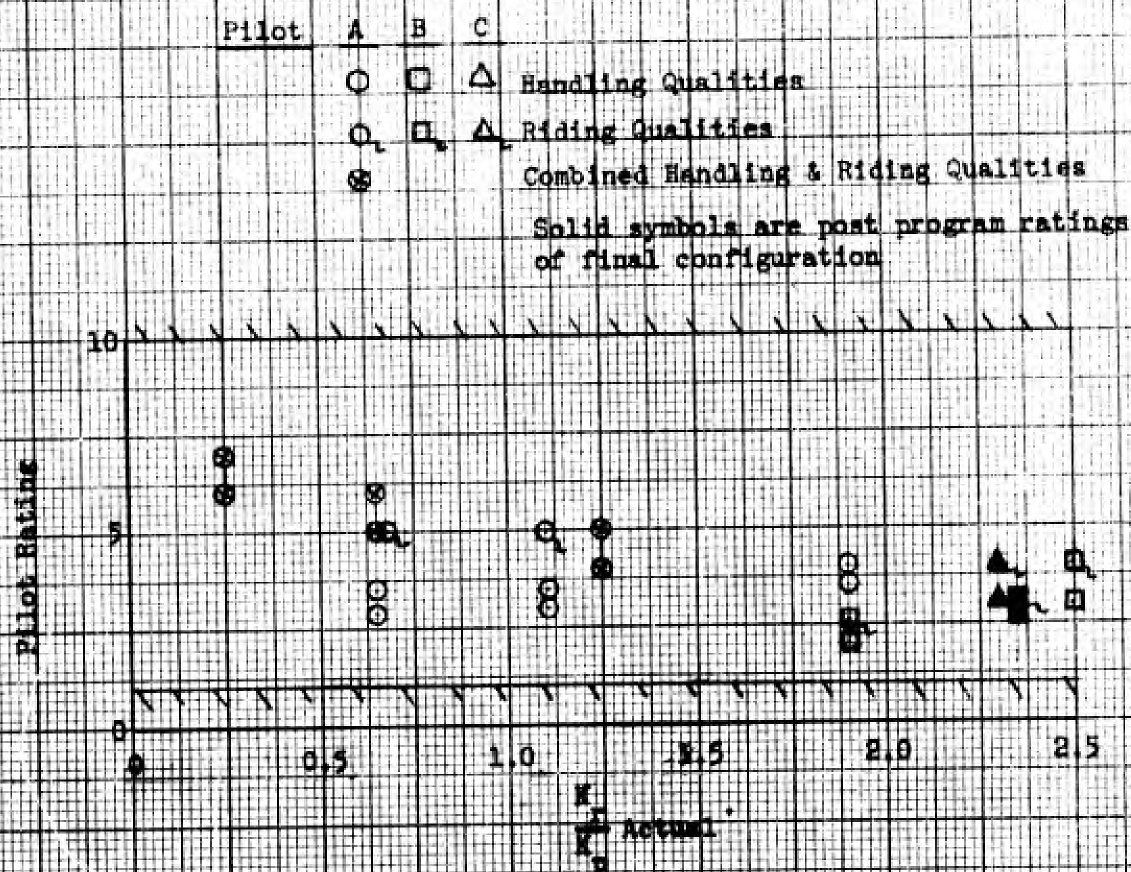


Figure 38. Lateral-Directional Pilot Ratings (Approach Phase)

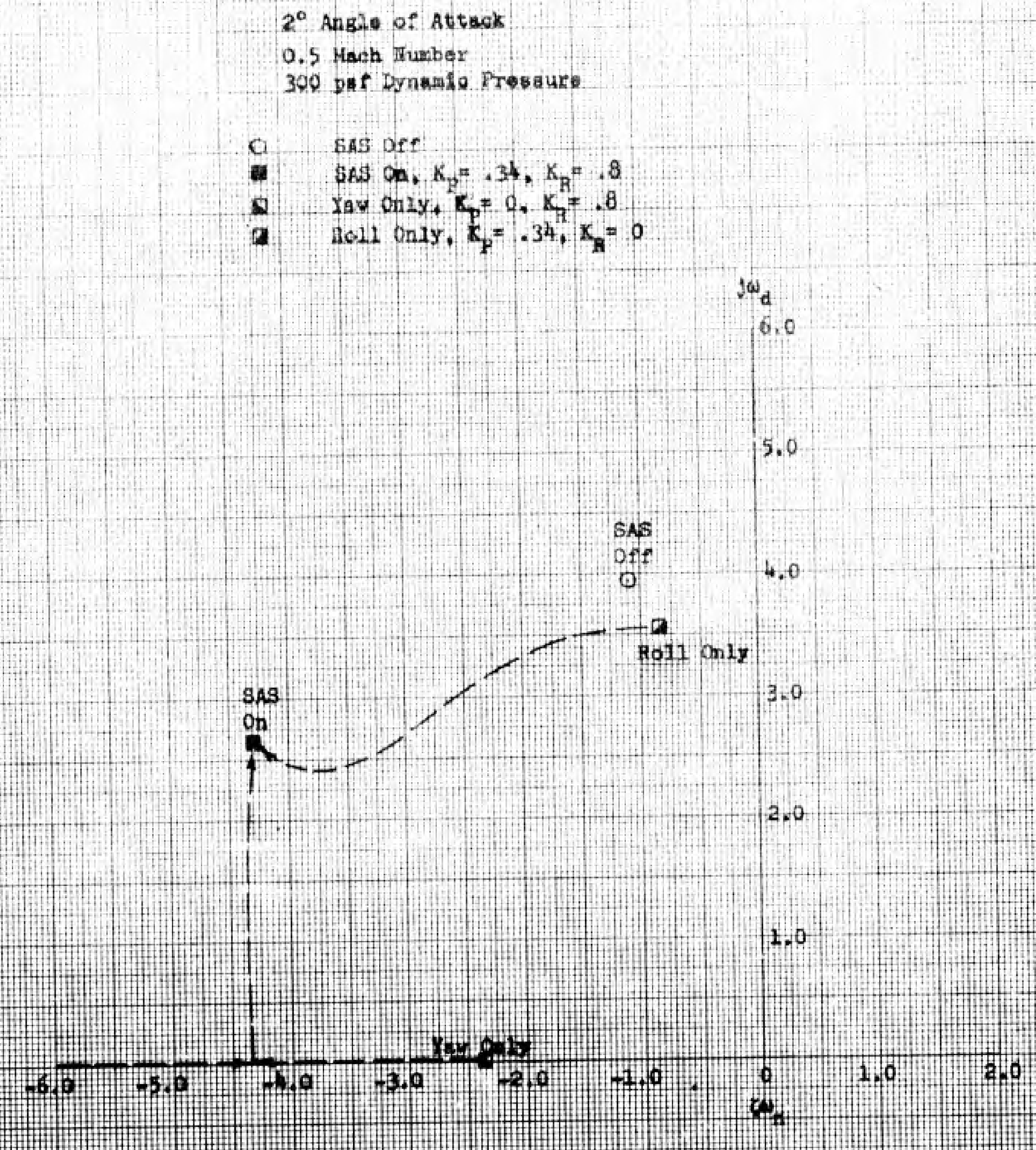


Figure 59. Effect of SAS Gains on Dutch Roll Characteristics in Final Configuration (Approach Phase)

Rudder Deadband

The lower flap control system linkage (pitch and roll) was equipped with spring cartridges which preloaded the system to minimize hysteresis. The rudder linkage was not similarly preloaded and a deadband of 0.1 degrees was measured in ground tests. It is possible that this very small deadband in the yaw axis may have allowed the roll SAS (which was destabilizing) to initiate or sustain small amplitude Dutch roll motions of the vehicle which could never be totally damped by the yaw SAS.

Turbulence

The unusually high dihedral effect of the X-24A resulted in an unusual response to turbulence. Side gusts which caused small sideslip excursions produced rather large and abrupt rolling accelerations. The pilot who was sitting well above the vehicle cg experienced both the lateral side force due to sideslip and a lateral acceleration contribution from the rapid rolling acceleration. These two forces were additive with the result that the pilot was more sensitive to the vehicle accelerations and rolling motions in turbulence than might be expected in a normal airplane. After Flight 3 the pilots were asked to attempt to separate the riding qualities from the handling qualities, if possible, and rate each separately. Pilot ratings of the riding qualities were consistently poorer than the corresponding handling qualities by 1/2 to 1-1/2 pilot ratings. As experience was gained with the X-24A, the pilots concluded that much of the discomfort and concern on the early flights was, in retrospect, related to the rather unusual rocking sensation in turbulence (poor riding qualities), rather than a serious handling qualities deficiency. The following is a pilot quotation after Flight 11:

> "It is something you would not associate with turbulence. It is not like flying through turbulence in any other airplane I have ever flown. It is a riding quality thing like you guys have been saying. You feel it in the seat of the pants more than anything else. You don't see much motion on the airplane, but you feel this back and forth--apparently a lateral g of some sort. I felt it twice and I know it was turbulence because it was about the altitude we hit turbulence on the way up. It was not a problem at all, but it might have been had I not known that this is what happens when you hit turbulence."

This can be seen in figure 38, where handling qualities and riding qualities values can be compared. Handling qualities after Flight 3 were rated at 3.5 or better, except for one flight. Once the pilots gained sufficient confidence in the basic approach handling qualities of the X-24A, they were able to "ride out" light turbulence upsets without undue concern except when in close proximity to the ground (see Landing Phase section). These upsets were usually of short duration and damped very quickly. Although the momentary roll rates sometimes reached 15 degrees per second, the bank angle upset was 8 degrees or less. Simulated turbulence was inserted into the X-24A simulator to evaluate the effects on vehicle motions. Although the motion cues to the pilot, and thus the PIO tendencies, were not present, the abrupt rolling response characteristics of the vehicle were apparent on the simulator. Pilot presentations of roll rate and lateral acceleration were tried on the fixed-base simulator in an effort to artificially reproduce the pilot cues. These efforts

to determine the pilots closed loop response to turbulence using the fixed-base simulator were unsuccessful.

Rate Limits of Lower Flaps

The upper and lower flap power actuators were designed to produce higher forces in the extend direction than in the retract direction, relying on aerodynamic hinge moments (which were always in the direction tending to close the flap) to provide the additional retracting force. As a result of this design, the maximum extend surface rate was approximately 60 degrees per second, and the maximum retract rate was only 20 degrees per second for low values of hinge moments. Before the first flight it was apparent that the expected first flight hinge moments would be only a fraction of the design values. The net affect of this rate difference would have been an uncommanded nose-down pitch input that would have resulted when a differential lower flap was commanded which exceeded the rate limit on the retracting flap. To prevent this possibility from occurring in flight, an orifice was added to the extend side of the lower flap actuators to slow the maximum extend rate to approximately 25 degrees per second. This change was made before the first flight. Due to the relatively low effectiveness of the lower flap in roll, large deflections were required for control and for damping. Simulator studies with the reduced surface rates showed that the rate limits would not be exceeded except for large and rapid pilot inputs. These simulator studies were performed without simulated turbulence. The effect of turbulence as observed on the first two flights was to cause continuous, relatively high frequency activity in the lateral axis, thus causing saturation of the flap actuators to occur momentarily on several occasions with only moderate pilot activity (figure 35). Simulator studies performed with turbulence levels similar to those observed in flight (by approximating observed sideslip vane activity with a random noise generator), confirmed that the lower flap saturation margins were noticeably reduced in turbulence.

As a result of this study it was realized that increased lower flap surface rates would be beneficial regardless of other factors. A geometry modification was made which essentially doubled the maximum surface rate, but reduced the maximum hinge moment capability. Flight hinge moment measurements and simulator studies had shown that the hinge moment capability of the revised linkage was safe and adequate for the planned test program. The overall effect of this modification was to increase the safety margins for approaches in turbulence. It did not significantly alter the handling qualities under still air flight conditions.

PIO Sensitivity

Throughout the program, whenever vehicle lateral motions were observed during the landing approach, lateral stick inputs were also observed which were phased approximately 180 degrees with roll rate (that is, the pilot stick motion was opposing roll rate). This tendency was observed with all of the pilots and for several different flight conditions. Hands-off maneuvers did not show any unintentional stick movements, however, thus eliminating the possibility of control system imbalance. Instrumentation was installed to measure lateral acceleration behind the pilot's head in an attempt to further identify the pilot cues during the approach. Although the measured acceleration magnitudes were

not large ($\pm 0.1g$) the phasing was nearly identical to that of roll rate, thus strengthening the pilots response to oppose roll rate with stick motions (figure 35). The pilot gain, in terms of commanded aileron deflection per degree-per-second roll rate, was calculated for several of these observed lateral motions and was found to be typically 0.5, increasing to approximately 1.5 just prior to touchdown.

Dutch roll pole locations for several key flights were computed using flight test derivatives and actual flight control settings. They are shown in figure 40 along with the effect of pilot gain (using a $\delta a/P$ transfer function) on the migration of the poles. A pilot gain of 0.5 significantly increased the frequency and reduced the damping slightly for the first flight configuration. The pole location for flight two was more lightly damped than the others due to the lower yaw and higher roll gain settings, but pilot gain produced only a small pole migration. The final configuration exhibited heavy damping with a vertical pole migration with pilot gain. The effect of KRA can be seen by comparing the pole migration for Flight 16 (flown with maximum KRA) with that of the final configuration (KRA programmed with angle of attack).

In an attempt to minimize the pilot's small amplitude activity in roll, the lateral break-out force and force gradient were both increased and a lateral stick damper was added. The effect of these changes could not be evaluated because of the other simultaneous changes that were made; however, it was felt to be a relatively minor improvement.

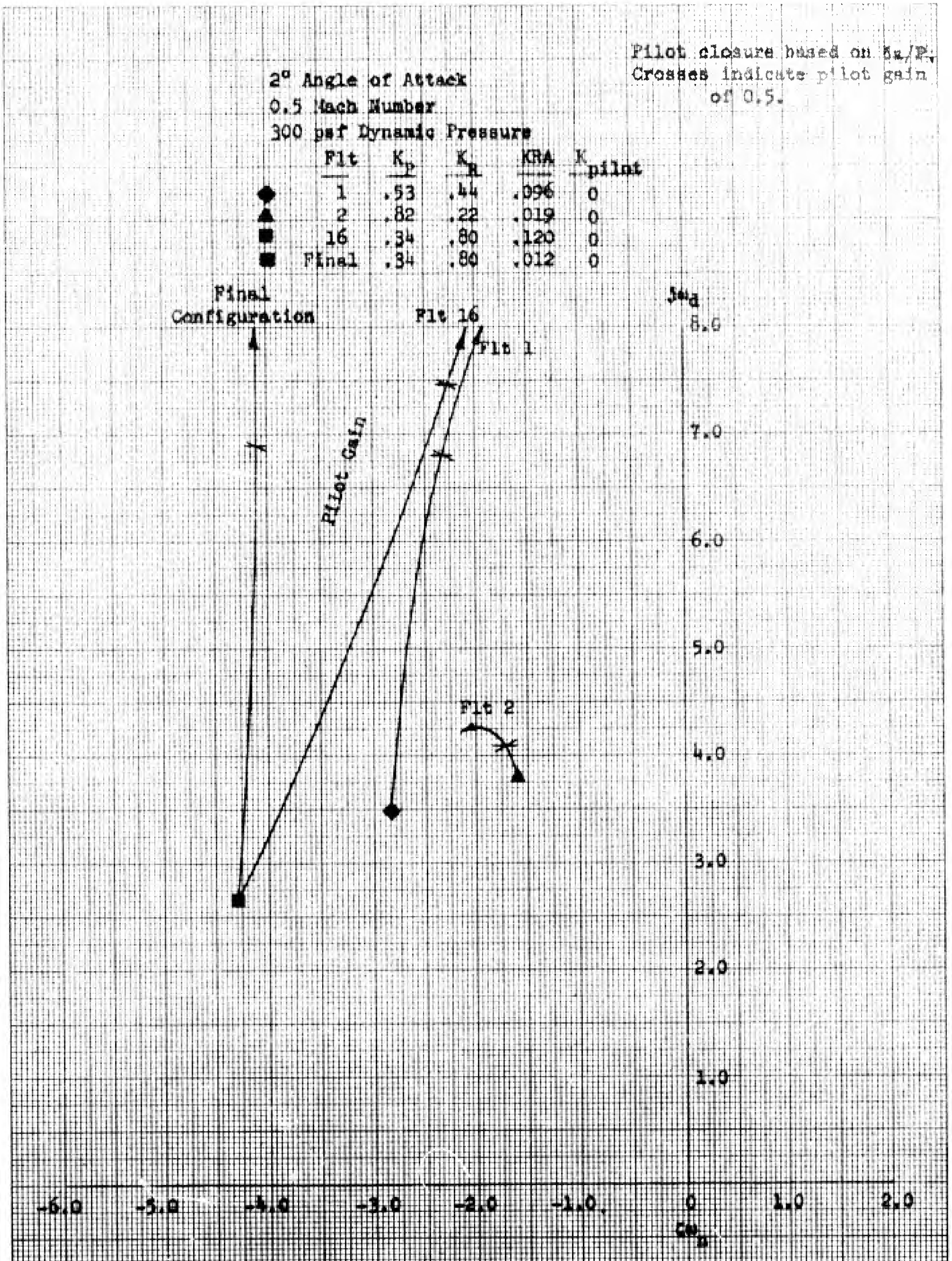


Figure 40. Effect of Pilot Gain on Dutch Roll Characteristics (Approach Phase)

Aileron to Rudder Interconnect

As indicated above, the interconnect was unintentionally locked at 0.096 during the first approach, but was operating along the design schedule with angle of attack on the second flight. Early indications of proverse $C_{n_{\delta_a}}$ prompted a reevaluation of the KRA versus α schedule to reduce the KRA in the low angle of attack regions (reference 4). The KRA intercept angle of attack was initially shifted from zero to +6 degrees so that the KRA remained at zero percent below 6 degrees angle of attack. As flights progressed into the transonic region where high values of KRA were required, the non-redundant nature of the KRA system caused some concern as to the "landability" of the X-24A with a hardover KRA malfunction. Progressive increases in KRA were tried on several approaches, and on Flight 16 the complete approach and landing were flown with the KRA at the maximum value for the -13° δU_B configuration of 0.23 (50 percent on the cockpit indicator) (figure 40). The following is a pilot quotation after the flight:

> "I did push over and get about 310 knots indicated. The airplane is more sensitive with KRA at 50, needless to say, but it sure is flyable. I don't know what it would be like in turbulence. I think you would probably have your hands full in turbulence with it like that. You probably will see on the traces quite a bit of small amplitude rolling throughout the pattern. I did not feel uncomfortable at all."

The final KRA versus α schedule which was used for all subsequent flights was essentially the same as for Flight 2. It could therefore be concluded that the interconnect setting had only a minor effect on the handling quality problem experienced on the first two flights· however, it should be emphasized that the destabilizing influence of KRA was directly related to the pilot gain, which was probably higher on early flights due to pilot apprehension and a lower level of confidence.

Previous Piloting Experience

Pilot A (who flew the first five X-24A glide flights) had previously flown the M2-F2 vehicle. Pilot B was also closely associated with the M2-F2 program, although he had never flown the vehicle. The M2-F2 exhibited a severe lateral PIO tendency in the angle-of-attack range only slightly below the approach angle of attack. Pilots were quite aware of their proximity to this PIO boundary on every M2-F2 landing and described the feeling as a "nibbling sensation". Severe PIO oscillations were experienced inadvertently on three different occasions during the M2-F2 test program and contributed to the landing accident which occurred on the last flight. With this background pilots A and B (especially A) were understandably wary of any small lateral motions during final approach on the early X-24A flights.

Following the first X-24A flight, pilot A described the approach as follows:

> "As the airspeed picked up I felt something that was very similar as the experience in the M2. You could start to feel the lateral nibbling and it was reasonably comfortable

while I was still banked up. My α was still around 4 or 5 but as soon as I rolled out and tried to push down to 2 α it was real apparent that I wasn't going to stay down there very long. To get a little bit better handling qualities I let the airspeed bleed off a little bit and I let α come up to about 5 and so we came in more about 270 knots rather then 300 knots as planned. I decided to use landing rockets at about that time."

As the pilots gained experience in the X-24A they recognized that the unusual riding qualities sensation in the X-24A was not associated with a severe handling qualities problem as was the case in the M2-F2.

Summary of High Speed Approach Handling Qualities

Errors in the wind tunnel predictions of the sign and magnitude of Cn_{δ_a} resulted in non-optimum roll and yaw SAS gains on early flights. The result was a lightly damped, relatively high frequency Dutch roll mode which was somewhat PIO prone. Turbulence produced rather unusual and uncomfortable rocking motions of the vehicle which gave rise to pilot apprehension, increased pilot gain, and thus further aggravated the PIO tendency. A combination of minor control system changes (primarily optimized SAS gains) and pilot experience in light turbulence resulted in very favorable pilot evaluations of the approach handling qualities on later flights.

Configuration Change

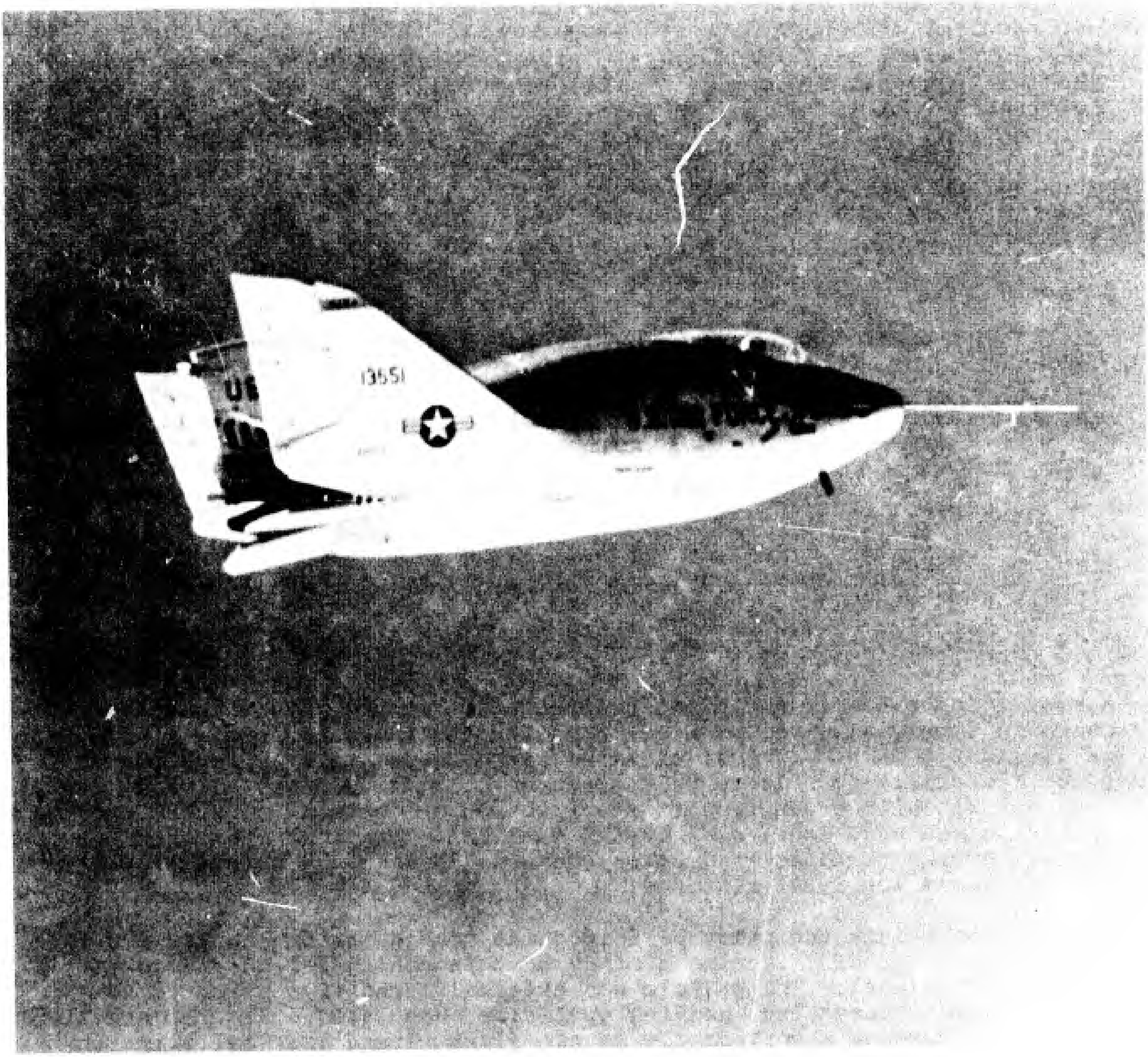
A lateral PIO was observed on several flights during the configuration change from -40 to -13 degrees upper flap and 0 to -10 degrees rudder bias. These momentary motions usually occurred while the pilot was concentrating on maintaining a constant angle of attack for test purposes. The following is a typical pilot comment after experiencing a slight PIO during the configuration change:

"I don't know what it is. I wasn't really pressed with any real aft stick positions. It was just that as I was trying to hold that 12° α that I noticed that I was moving the stick. It was kind of funny. The funny thing was that I don't recall any aircraft motion."

A root locus plot for a typical configuration change flight condition is shown in figure 41. The pole position for the basic vehicle with the SAS on is lightly damped. Pilot closures proportional to roll rate are seen to be destabilizing. It is felt that the pilot's gain was probably higher than normal while attempting to stabilize on an angle of attack. The situation was also aggravated by the fact that the pilot was asked not to trim during these configuration changes, thus he was holding some amount of continuous longitudinal force.

On one flight the pilot performed the configuration change with the roll and yaw SAS off. A time history of this configuration change is shown in figure 42. The vehicle was extremely sensitive prior to the configuration change and handling qualities were rated 6.5. The handling qualities improved significantly as the flaps closed and, following the

configuration change, were rated 3.5. A root locus plot of the Dutch roll pole locations with SAS off, both before and after the configuration change, is shown in figure 43. Note that the basic airframe exhibited very light damping in both cases. Pilot closures proportional to roll rate were destabilizing for the -40° δU_B configuration and caused divergence for pilot gains greater than 0.5. For the -13° δU_B configuration, pilot closures had little effect on the Dutch roll damping, and did not produce divergence even at high pilot gain. The primary reason for the observed difference in the SAS-off characteristics before and after the configuration change, was the result of a mechanical reduction in the interconnect ratio associated with the flap bias system, rather than an aerodynamic effect. The broken line shows what the pilot closures would have been for the -13° δU_B configuration data if the actual interconnect ratio had remained the same.



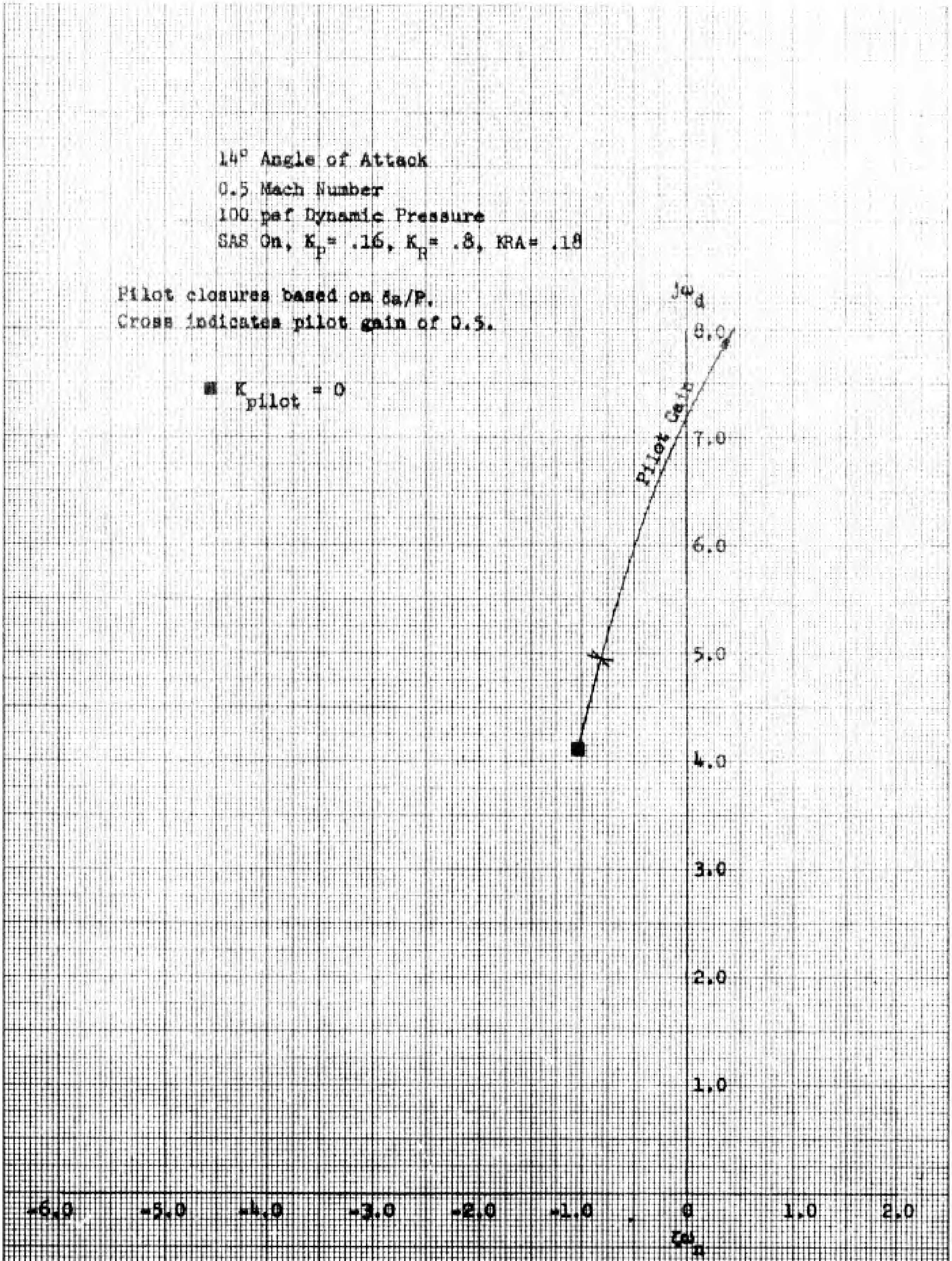


Figure 41. Effect of Pilot Gain on Dutch Roll Characteristics During Configuration Change (SAS On)

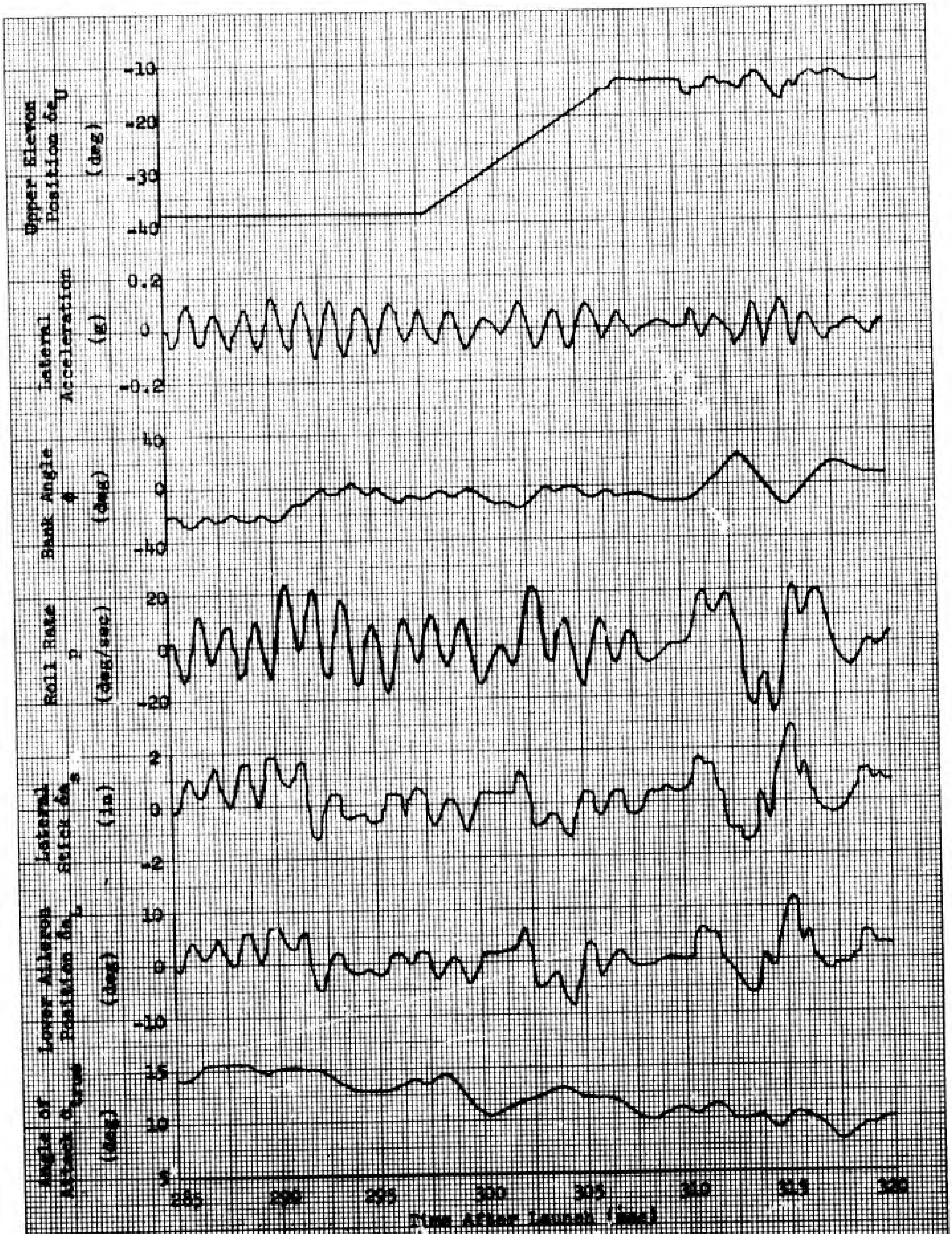


Figure 42. Time History of Configuration Change with SAS OFF

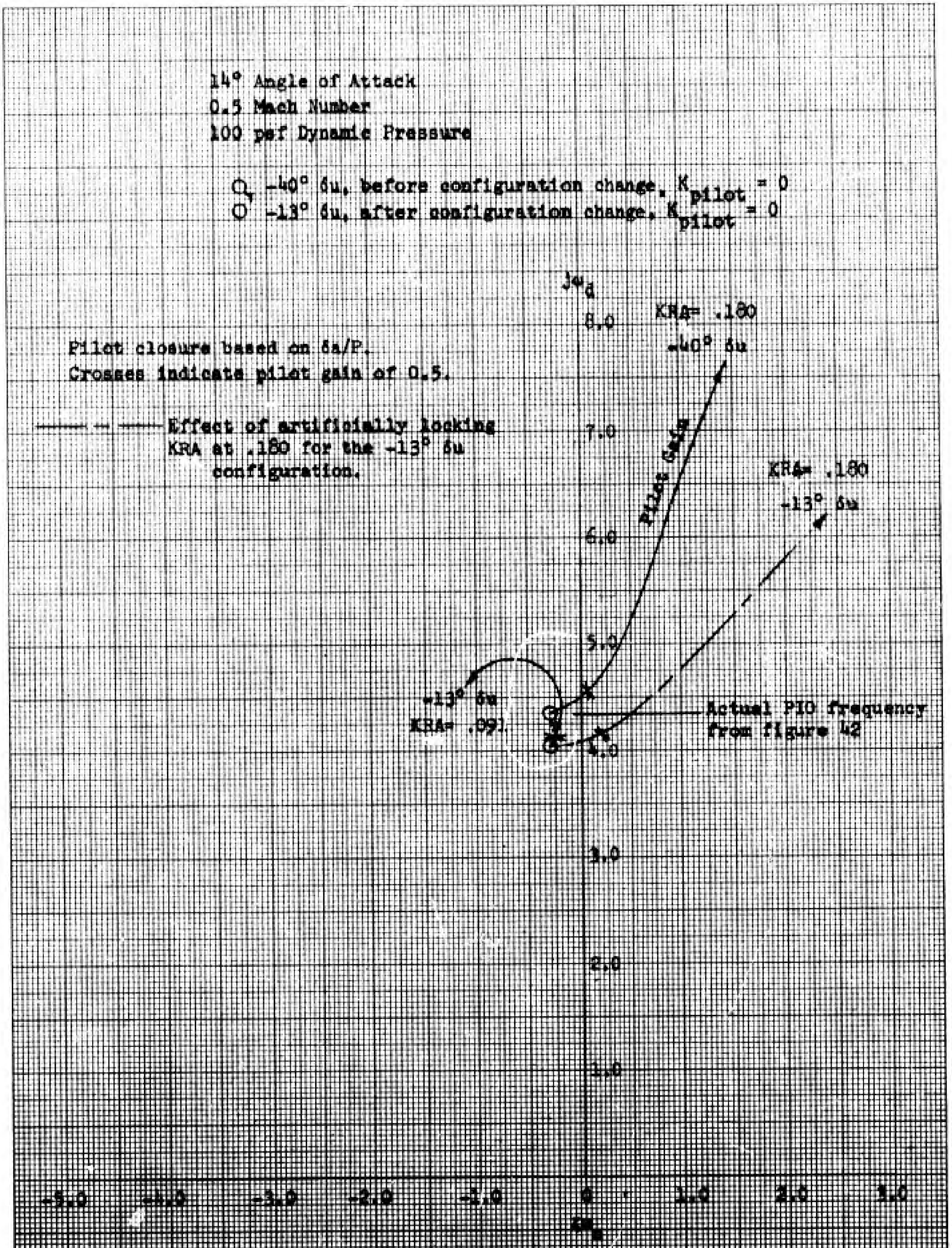


Figure 43. Effect of Pilot Gain on Dutch Roll Characteristics During Configuration Change ([illegible])

SAS-Off Characteristics

Although none of the actual high airspeed approaches were flown without SAS, the pilots did evaluate the SAS-off handling qualities at high altitude and low to medium airspeeds and felt that successful landings could have been performed in smooth air. The Dutch roll pole locations and pilot roll rate closures are shown in figure 44 for the basic vehicle without SAS. It was anticipated that the effects of turbulence without SAS would have been quite severe.

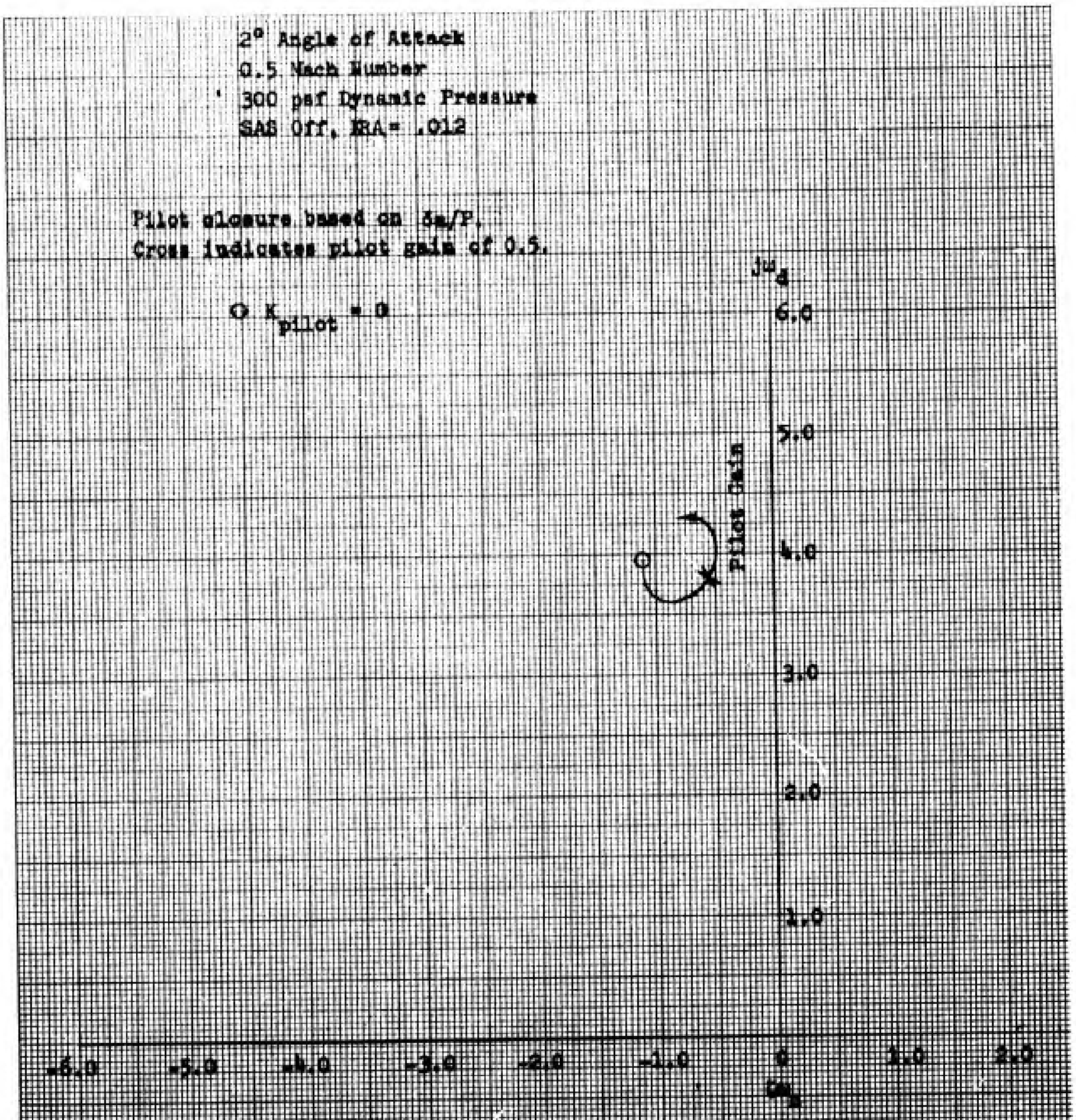


Figure 44. Effect of Pilot Gain on Dutch Roll Characteristics with SAS Off (Approach Phase)

Upper Flap Approaches

Two approaches were flown during the program using the upper flap for pitch and roll control. Before these flights there was concern over the potential of a pitch PIO due to the combination of higher effectiveness of the upper flap and the increased stick gearing resulting from the upper flap bias system. The approaches were therefore planned for 270,rather than 300 knots IAS as on other flights. The handling qualities on these two approaches were described as excellent, with pilot ratings of 2. Airspeeds of 290 knots IAS were reached and no PIO tendencies were noticed, although the pilots were aware of the higher sensitivity in the roll axis. The following is a quotation after an upper flap approach:

> "Although the airplane is a little more responsive in roll, the pilot ratings and the comparisons with the other configuration are pretty much the same. I didn't notice any difference in pitch sensitivity. The only one that I really noticed was roll. I got turbulence at least three times, pretty good turbulence coming downhill, and each time it was just a pure roll thing--about three cycles and quit. And the airplane was just as solid as a rock. It was really, I think, a much better ride with this configuration than it is with the lower flaps. I couldn't feel any side motion like we had felt before."

A root locus plot using the flight test upper flap derivatives is shown in figure 45. Although both the handling and riding qualities were slightly better using the upper flaps for control, the lack of speed brake capability in this configuration resulted in a decision to return to the -13 degree upper flap configuration for landing approaches.

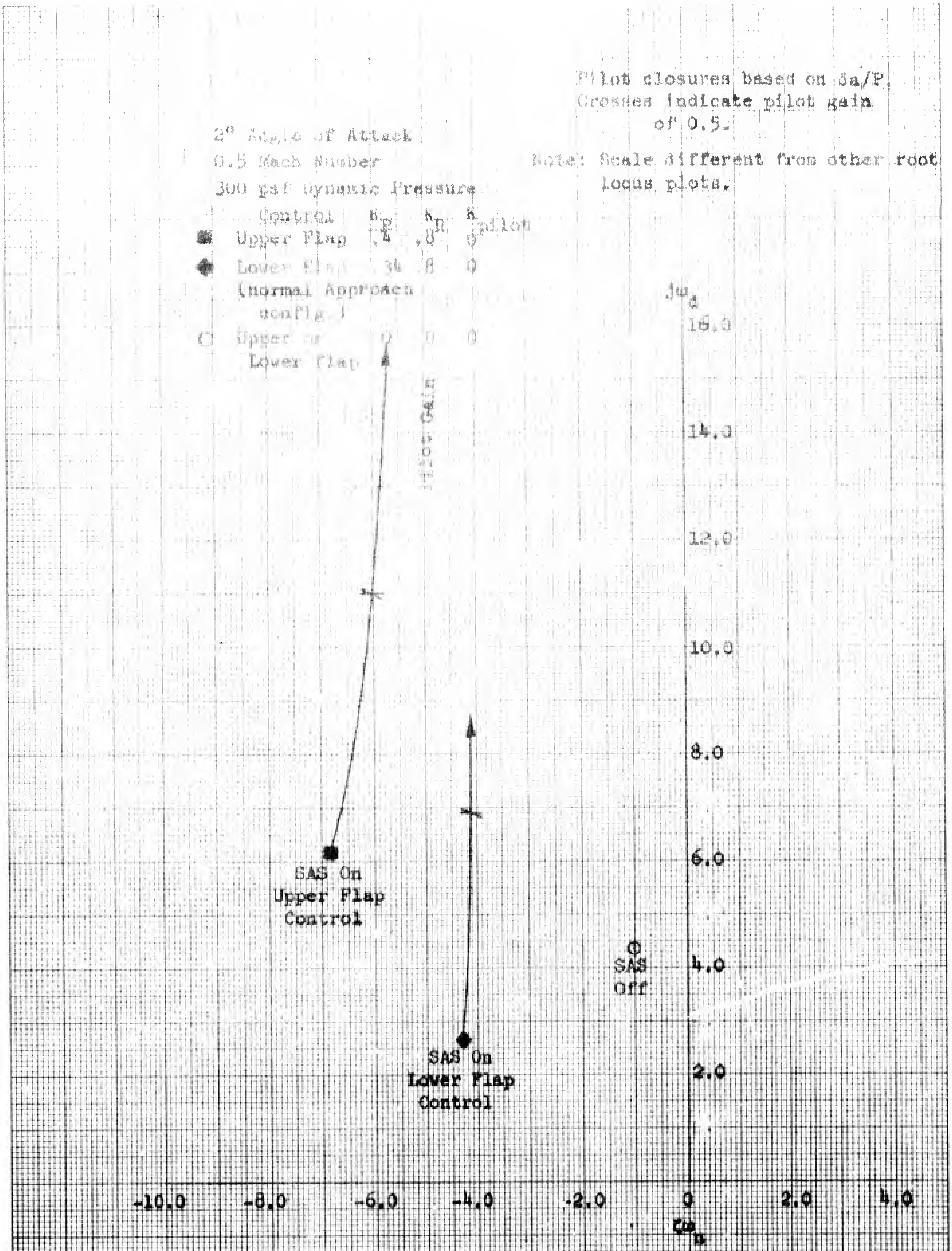


Figure 45. Effect of Pilot Gain on Dutch Roll Characteristics for Upper Flap Approaches (SAS On)

LANDING PHASE (Flare to Touchdown)

The handling qualities of the X-24A during the flare and landing were influenced by the effects of turbulence and crosswinds and by the nose-down trim change associated with gear extension.

Configurations Flown

Landings were performed in three different control system configurations. The lower flaps were used for pitch and roll control during the entire flight for the first seven glide flights. Most of the remaining flights were flown using the lower flaps during the approach and flare, crossing to the upper flap at gear extension, with the actual landing performed using the upper flaps. Two flights were made with control by the upper flaps for the entire flare and landing. A complete description of the X-24A approach and landing technique and a summary of the performance aspects of the landings can be found in reference 6.

Longitudinal Handling

The longitudinal handling qualities during the flare were considered excellent by all of the X-24A pilots. The flare was performed with little conscious effort by the pilot for all of the configurations flown.

The landing gear was extended near the end of the flare at an altitude of 100 feet or less. Both the nose and main landing gear pivoted forward at extension, causing the cg to move forward by 0.72 percent. An aerodynamic nose-down trim change also accompanied the gear extension. The combined additive effects of the cg and aerodynamic trim change were very apparent to the pilot and disconcerting when close to the ground. A slight delay between the deployment of the landing gear handle and the actual pitch trim change made it difficult for the pilots to compensate for the trim change smoothly. The amount of stick movement required to arrest the pitch-down is shown in figure 46. Minor modifications to the nose gear door and the change to the lower-to-upper-flap crossover technique at gear extension reduced the required stick movement somewhat. Flights 19 and 20 were the only flights on which the gear deployment was controlled entirely through the upper flaps. Notice that the stick deflections were only 1-1/4 inches. Neither pilot could remember experiencing the gear transient on these flights. Pilot ratings for control of the gear transient are shown in figure 47. Ratings improved slightly during the course of the program due to the changes mentioned above and the pilot's familiarity with the vehicle.

In the final configuration (crossover to upper flap at gear extension) the pilots often encountered a brief 2 or 3 cycle pitch PIO of small magnitude immediately after gear extension. This momentary oscillation was felt to be a result of the abrupt transfer of control to a more effective control surface, which required a brief period for the pilot to adapt to the higher sensitivity.

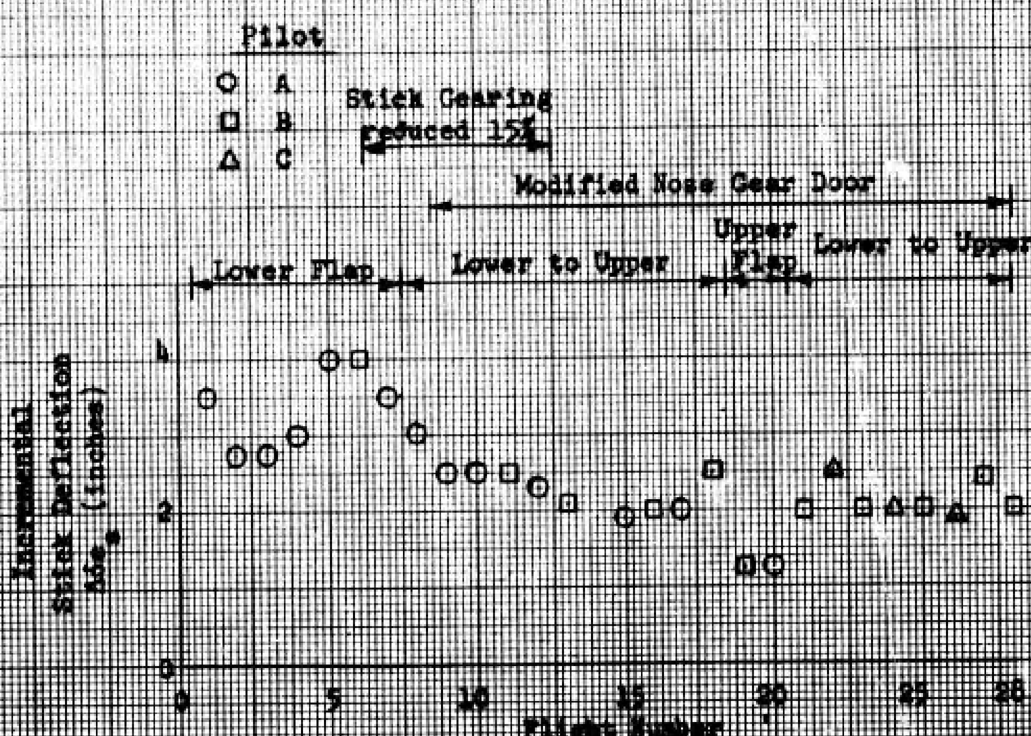


Figure 36. Longitudinal Trim Change due to Landing Gear Extension

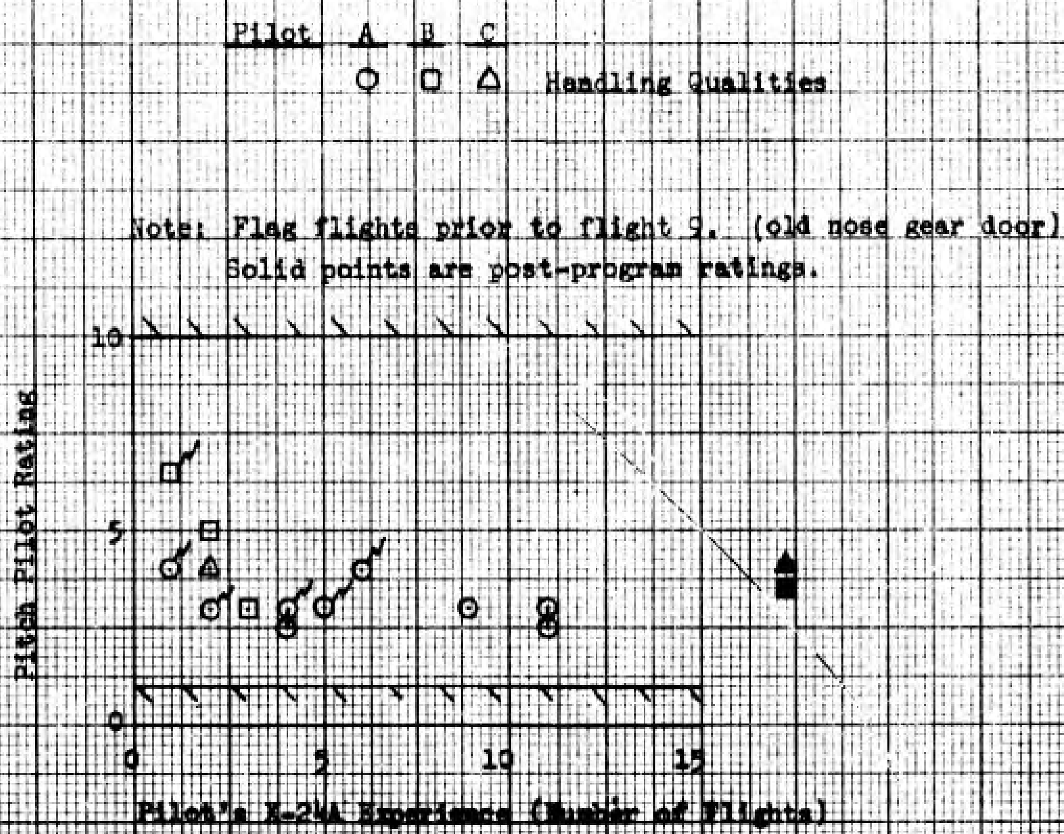


Figure 47. Pitch Pilot Ratings of Landing Gear Transient

Lateral-Directional Handling

The lateral-directional handling qualities during the flare were similar to those discussed for the approach. Small turbulence upsets were more common during the final approach and flare than during the higher altitude portions of the approach. These upsets on the first two flights caused some concern and resulted in use of the landing rocket during the flare, as discussed earlier. After the first few flights the pilot did not experience any lateral-directional control difficulties during the flare.

Lateral stick activity by the pilot increased after gear extension, as the vehicle slowed and the angle of attack increased. On the first flight the combination of pilot and SAS activity caused saturation (rate limiting) of both lower flaps just before touchdown. Simulator studies showed that increasing the roll gain and reducing the yaw gain would stabilize the vehicle attitude at the touchdown condition, and thus avoid rate limiting of the surfaces. Although this gain combination did minimize the rate limiting near touchdown on the second flight, it was found to have the opposite effect during the high speed approach. The modification to increase the lower flap surface rates eliminated the rate limiting problem for both conditions.

All landings after Flight 7 were accomplished while using the upper flaps for control. The Dutch roll pole locations and effect of pilot gain are shown in figure 48 for the condition just after gear deployment ($6°\alpha$, 200q) and just before touchdown ($14°\alpha$, 100q). Both conditions are seen to be well-damped. Pilot inputs provided some additional stabilization. Lateral control power was higher with the upper flaps than with the lower flaps, and quite adequate for landings in still air. The abrupt rolling motions of the X-24A in turbulence, however, created a requirement for additional roll power, especially when close to the ground. Pilot ratings for the lateral-directional handling qualities at landing are shown in figure 49. The rating of 8 was associated with a turbulence upset just before landing in a 10-knot crosswind. The pilot felt that he did not have adequate roll power to control the vehicle during and immediately after the upset. The pilot commented:

> "And then from gear extension on down was probably the worst part of any flight I've had. We had a good crosswind. I could feel having to put a wing down to keep the airplane lined up. And then shortly before touchdown the airplane did a rapid roll in one way, and I recovered from it and brought it back down and got the wheel down. Touched down one wheel first, and I don't really know what happened from there on. Something. It went back down on one gear, and it started to go a little bit sideways. And it felt like it came back up off the ground again. And then back down on this wheel, and it heeled over to the right. And it started cutting off to the right, and I couldn't do anything with it. I was just riding along."

In general, the pilots felt that the lateral-directional handling qualities of the X-24A during the flare and landing were excellent on a calm day with a rating of 2.5 to 3. The handling qualities deteriorated rapidly, however, with crosswinds and/or turbulence due to the mismatch between the high dihedral effect and relatively low lateral control power. Controllability of the vehicle during the ground rollout after touchdown was also strongly influenced by crosswinds and is discussed in reference 6.

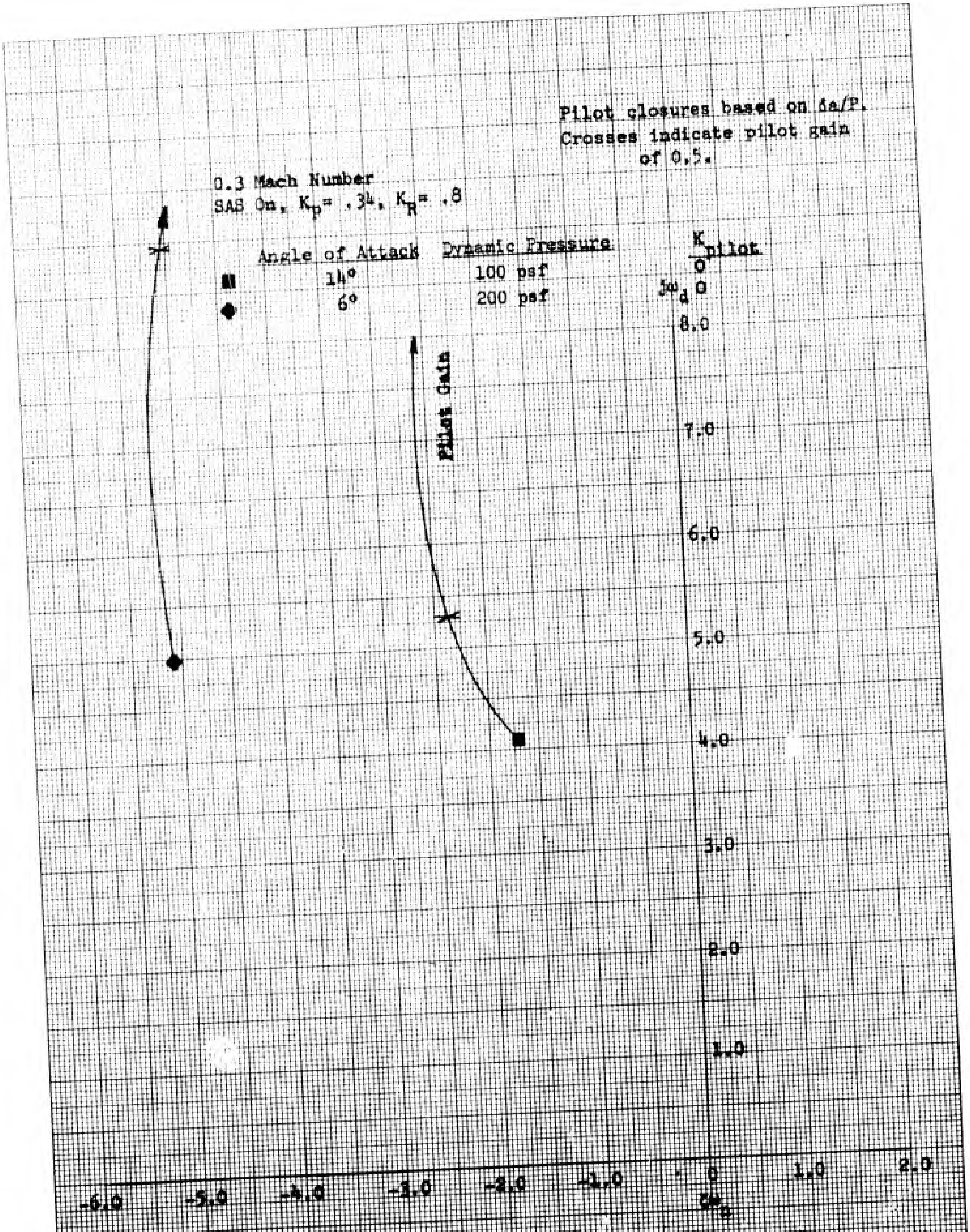


Figure 48. Effect of Pilot Gain on Dutch Roll Characteristics (Landing Phase)

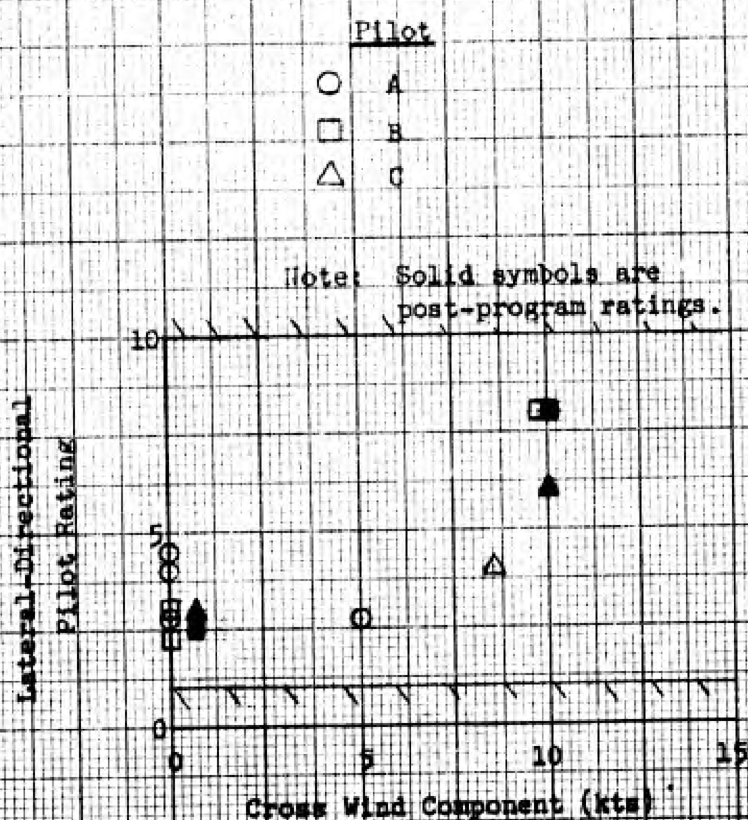


Figure 49. Lateral-Directional Pilot Ratings of Landings

CONFIRMATION OF HANDLING QUALITIES BOUNDARIES

The controllability boundaries were modified during the program as flight test stability derivatives were obtained. The final boundaries are shown in figure 50, using the same criteria and technique as discussed under Preflight Handling Qualities, but using simulator stability derivatives that were adjusted to flight test values.

Comparison between figures 9 and 50 shows the reduced transonic angle-of-attack corridor which resulted from the C_{n_β} being lower than predicted.

During the flight test program the handling characteristics near the boundary conditions were confirmed qualitatively by asking the pilot to either cautiously approach the boundary angle of attack at a prescribed Mach number during a flight, or by intentionally altering the KRA or flap setting so that the control boundary momentarily moved into the mid angle-of-attack range.

In several cases, while flying close to the roll reversal boundaries the pilots reverted to the use of rudders to increase the rolling capability. This was usually a subconcious effort by the pilots, as they were unaware that they had used the rudders until they reviewed the data after the flight.

The abrupt transonic Mach limits associated with the approach and landing configuration (figure 9) were not confirmed during the test program due to the potentially catastrophic effects if the boundary were to be exceeded. Affected stability derivatives (C_{n_β} and C_{ℓ_β} primarily) were found to be similar to predictions in the subsonic Mach range. The tip fin flow separation phenomenon, which was felt to be responsible for the critical reductions in C_{n_β} and C_{ℓ_β}, were also observed in other less critical flight configurations. It was therefore concluded that the predicted approach configuration boundaries were valid. Planned flights usually called for the configuration change to occur at or below 0.55 Mach number and 30,000 feet, and pilots were advised to always maintain at least -30 degrees upper flap deflection when above Mach 0.7 (reference 2).

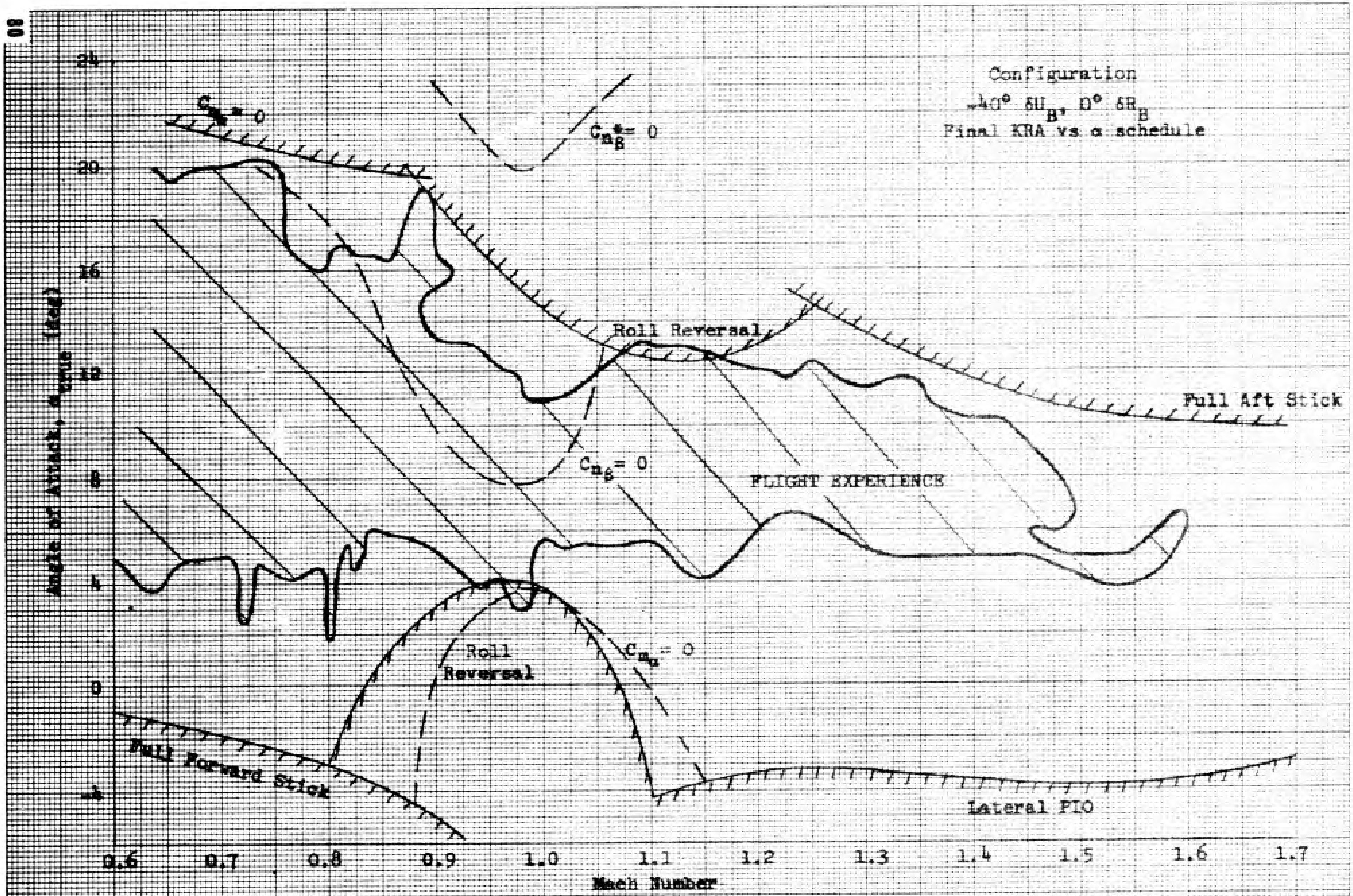


Figure 50. Final X-24A Controllability Boundaries

COMPARISON WITH PROPOSED SPECIFICATION (AFFDL-TR-71-64)

GENERAL

The extremely short duration of a typical X-24A flight, and the highly transient flight conditions, precluded the performance of many of the classical handling qualities maneuvers.

The step aileron inputs, full deflection aileron rolls, and steady state sideslips were impractical flight test maneuvers for a vehicle of this type. These maneuvers would have been quite time-consuming and would not have been compatible with the energy management requirements of a gliding vehicle.

Flight test maneuvers were performed for the purpose of obtaining stability derivatives and lift and drag data. These maneuvers (control doublets, pulses, and pushover-pullups) resulted in sufficient data to formulate a fairly accurate mathematical representation of the vehicle, which was suitable for evaluation against some of the proposed specification requirements. Since stability test maneuvers were obtained over a representative portion of the flight envelope the actual derivative data points from each individual test maneuver were used for an overall summary of conditions flown. The test data points are tabulated in reference 5. Faired curves of lateral-directional flight test derivatives obtained from control doublets, and longitudinal trim curves obtained during pushover-pullup maneuvers were used for portions of this evaluation and are shown in appendices II and IV.

ANALYSIS TECHNIQUE

A total of 127 flight test maneuvers were analyzed for the extraction of stability derivatives (reference 5). For each maneuver the exact test conditions and extracted stability derivatives for that particular maneuver were used as inputs to a computer program which solved for the roots of the characteristic equation.

It is emphasized that the response characteristics thus obtained were not direct measurements from maneuver time histories, but were computed responses based on stability derivatives that were extracted from the actual test maneuver. Since the derivative extraction technique required that the flight response time histories be matched by a computed model response, the frequency and damping characteristics of the computed model were essentially the same as those of the test maneuver. Advantages of this technique over direct measurement were the ability to recompute response characteristics for constant values of dynamic pressure as opposed to the rapidly changing conditions often experienced during actual test maneuvers, and the ability to compute both SAS-on and SAS-off responses from a single test maneuver. The resulting roots for longitudinal and lateral-directional maneuvers are plotted in figures 51, 52, and 54 through 59. Two sets of roots, SAS-on and SAS-off, were computed for each test maneuver. The configuration of the SAS during the actual test maneuver is depicted by the symbols. Note that these figures are summary plots of all of the maneuvers flown during the program, without regard

to flight condition or configuration. Specification limits from reference 9 are also shown along with the range of post-program pilot ratings when applicable.

The simulator was continually updated during the program by using the flight-test-determined stability derivatives. As an alternate technique for obtaining the necessary data for the step aileron inputs, aileron rolls, and steady sideslips, these maneuvers were performed on the updated simulator at selected constant flight conditions and the time history records were analyzed according to the procedures outlined in reference 9. Results of the simulator studies are shown in figures 60 through 62.

In applying the requirements of reference 9 the X-24A was considered a Class IV experimental vehicle. SAS-on characteristics were compared with level 1 requirements and SAS-off characteristics with level 2 and 3 requirements.

LONGITUDINAL SHORT PERIOD MODE

The frequency and damping of the longitudinal short period mode were within specification requirements with the pitch damper off over the range of test maneuvers (figures 51 and 52).

With the pitch damper on the n_z/α was slightly below the minimum level 1 requirement for three test conditions, and the short period frequency was above the maximum requirement for several high q conditions. Damping was within specification requirements with the pitch damper off. No supersonic pitch maneuvers were performed.

MANEUVERING FLIGHT

The X-24A flight controls consisted of a simple bungee feel system with an irreversible hydraulic system and various gearing linkages. The relationship between stick force, stick position, and flap position was therefore always predictable from ground calibration information. Measured trim curves (appendix IV) in combination with lift curve data from reference 1 were used to compute stick force per g for several flight conditions. The resulting points are plotted in figure 53 and are seen to be within specification limits except for two supersonic flight conditions.

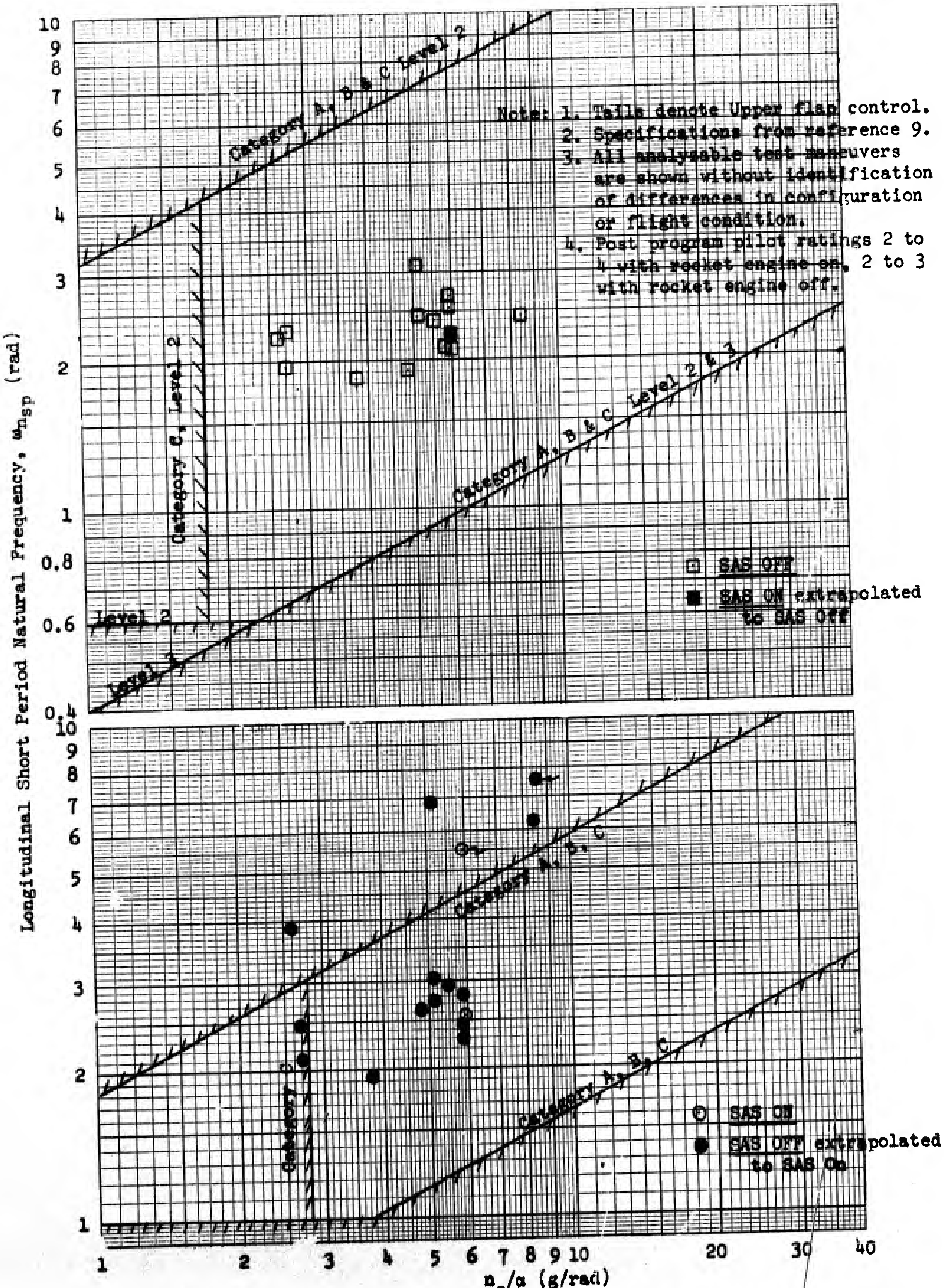


Figure 51. Longitudinal Short Period Frequency Characteristics (Transonic and Approach Phase)

Note: 1. Tails denote upper flap control.
2. Specifications from reference 9.
3. All analyzable test maneuvers are shown without identification of differences in configuration or flight condition.
4. Post program pilot ratings 2 to 4 with rocket engine on, 2 to 3 with rocket engine off.

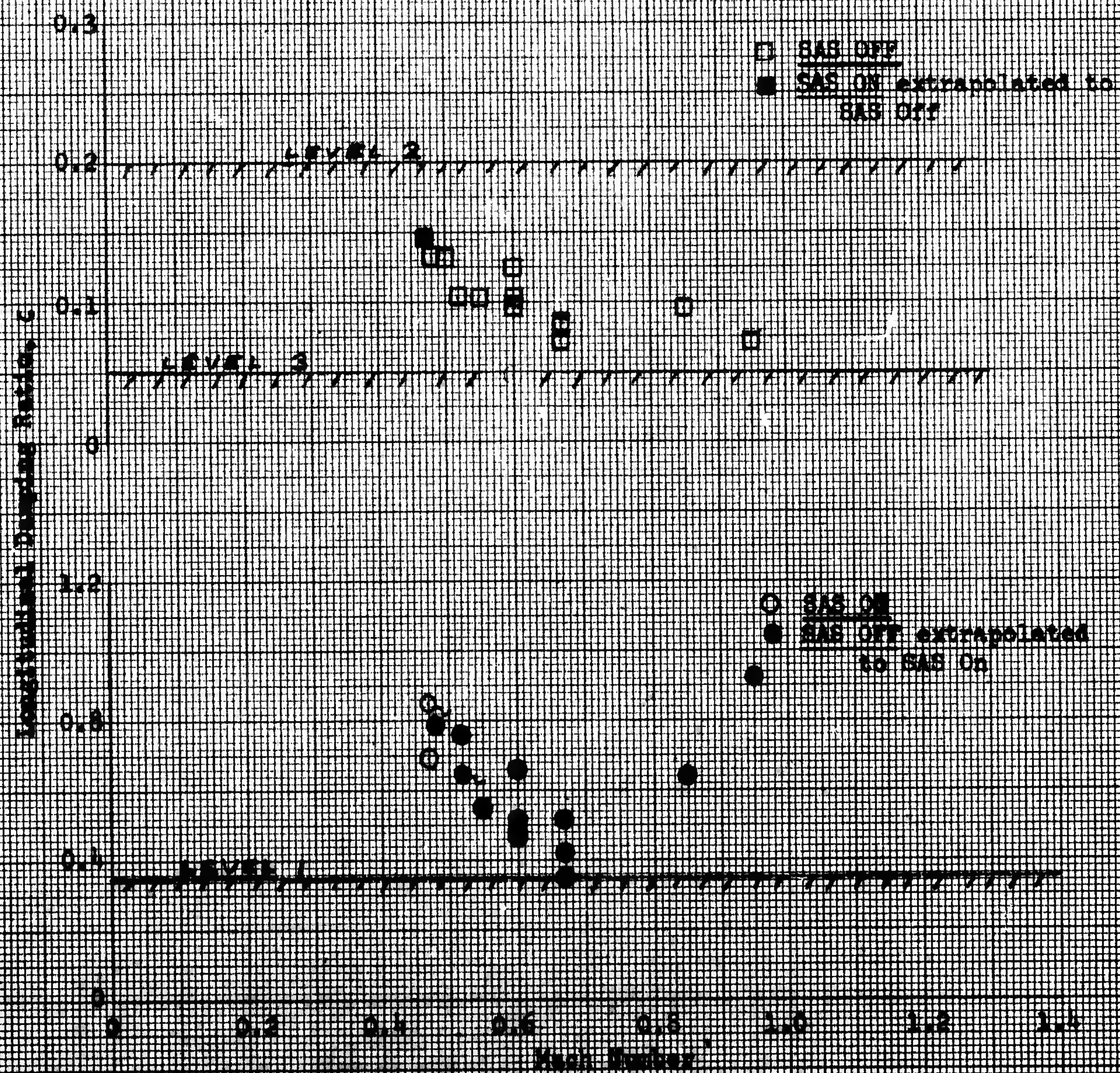


Figure 56. Longitudinal Short-Period Damping Characteristics (Transonic and Approach Phases)

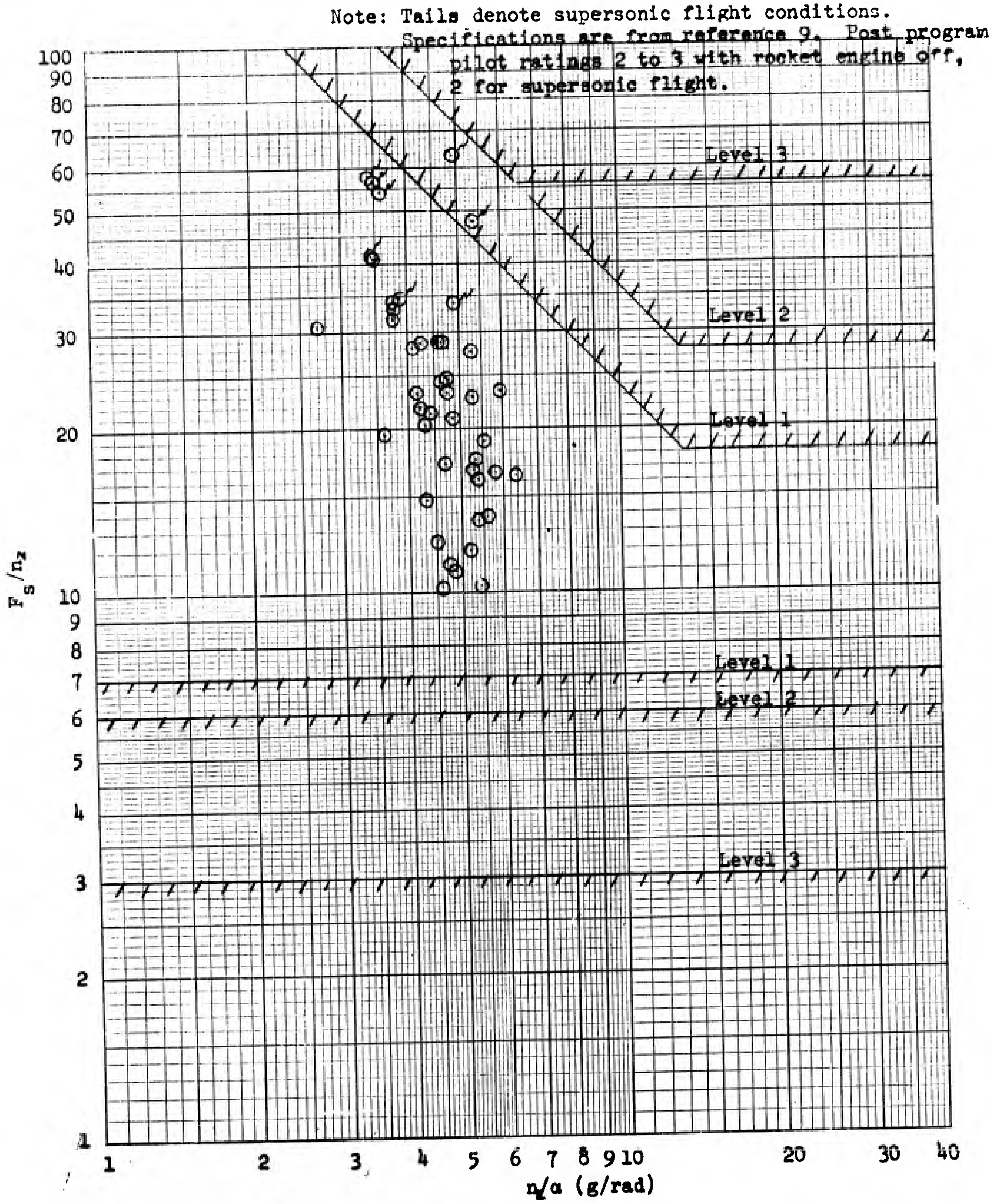


Figure 53. Longitudinal Stick Force per g

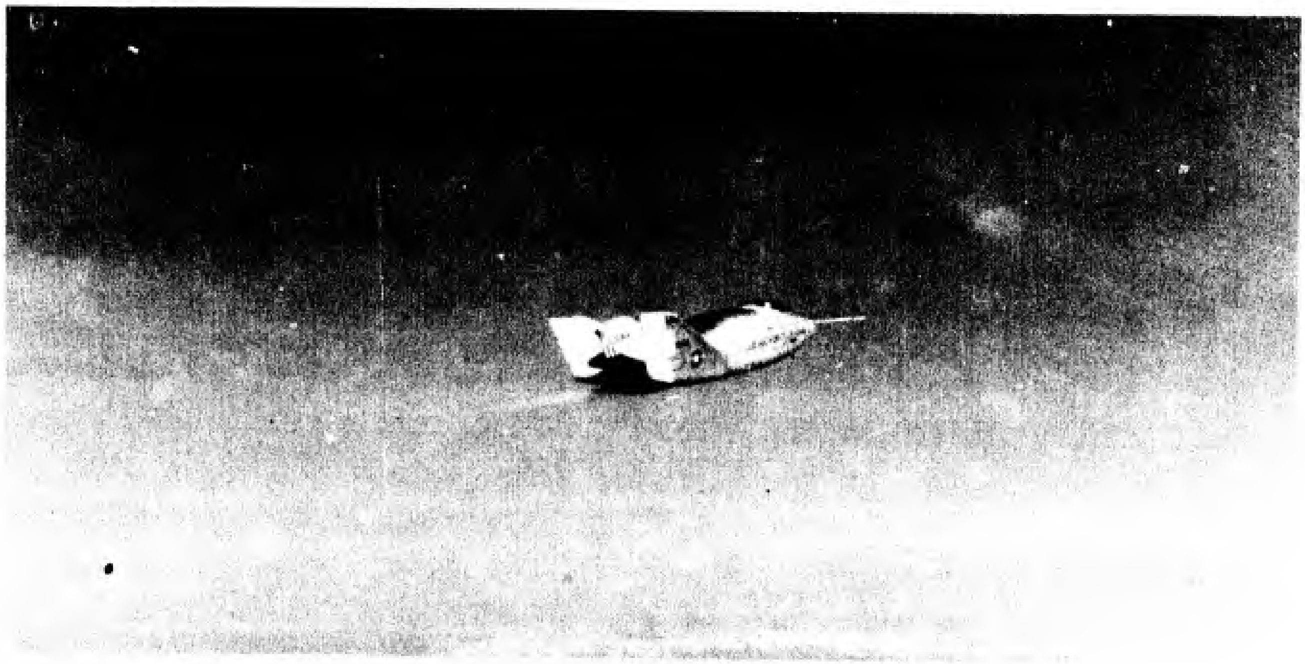
LATERAL-DIRECTIONAL SHORT PERIOD MODE (DUTCH ROLL)

The values of Dutch roll frequency and damping ratio for the test maneuvers flown are within specified limits for both dampers-off and dampers-on configurations (figures 54 through 58).

ROLL AND SPIRAL MODES

The same technique used for analyzing the Dutch roll characteristics was also used to determine roll and spiral mode time constants for all stability derivative test maneuvers. All SAS-off conditions exhibited an oscillatory, coupled roll-spiral mode (lateral phugoid) which is not permitted by the specification. The computed lateral phugoid mode had a period of 20 seconds or greater, with light to moderate damping (figure 59). This mode was never observed in flight due to the short SAS-off time segments, although test maneuvers confirmed values of the derivatives that contributed to the lateral phugoid (C_{n_p}, C_{n_β}, C_{ℓ_β}). For most flight conditions, the effect of normal SAS gain settings on the roll and spiral modes for the X-24A was to divide the lateral phugoid into the more common, non-oscillatory roll and spiral modes. Nearly all of the SAS-on characteristics computed for test maneuvers were non-oscillatory and within specifications. Through the improper selection of gains it would have been possible to produce an unstable coupled roll-spiral mode. Consideration was being given to intentionally missetting the SAS gains on later flights to explore the effects of the lateral phugoid; however, this was never done and the actual SAS gains that were flown during the program were chosen so as to avoid the coupled roll-spiral mode whenever possible.

For low angle of attack and high dynamic pressure flight conditions, the roll mode also combined with a surface actuator mode to form a high frequency, highly damped (by greater than 0.7), oscillatory mode which was similar to, and often had a direct influence, on the Dutch roll mode.



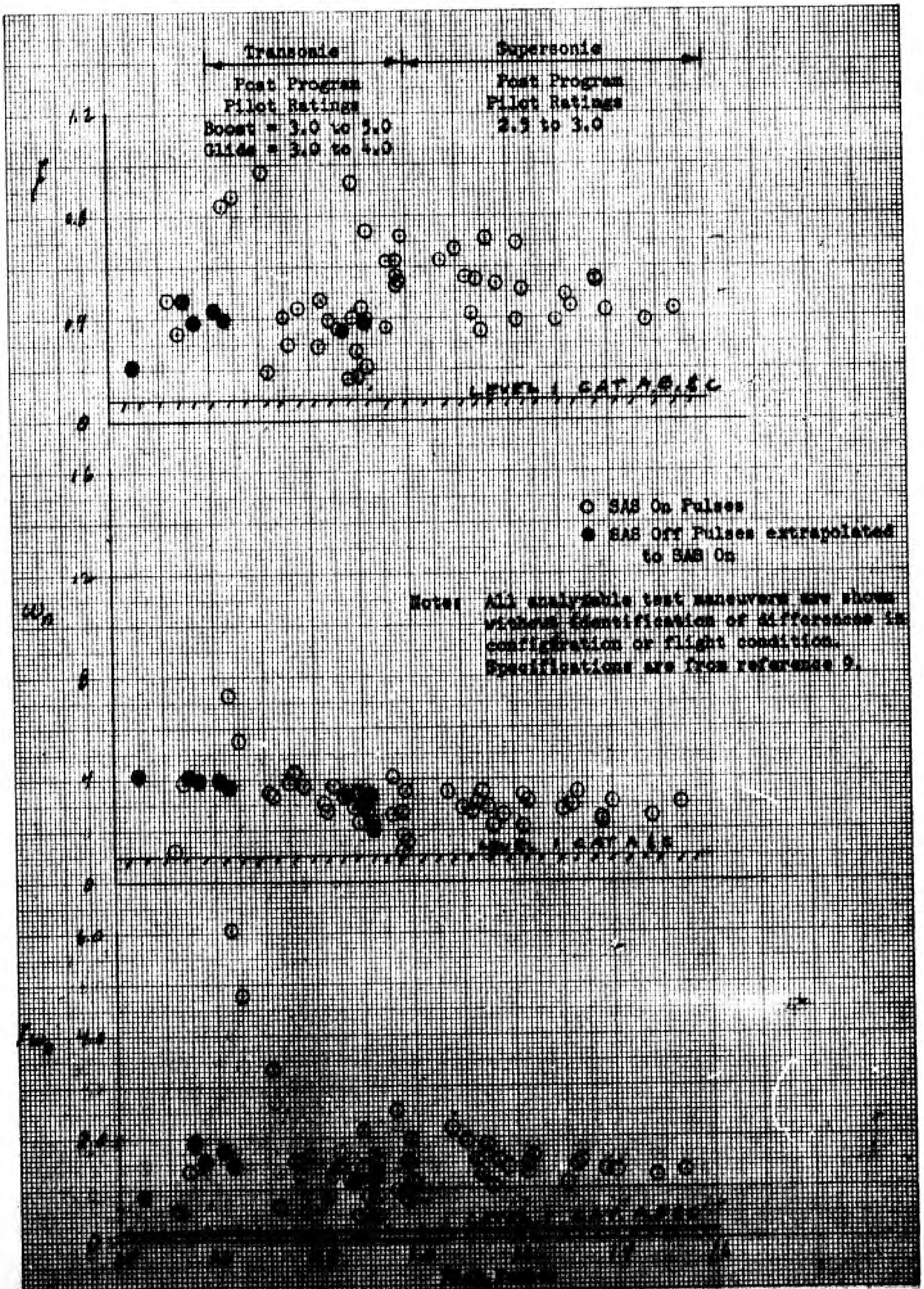


Figure 54. Flight Test Dutch Roll Characteristics (Transonic and Supersonic - SAS ON)

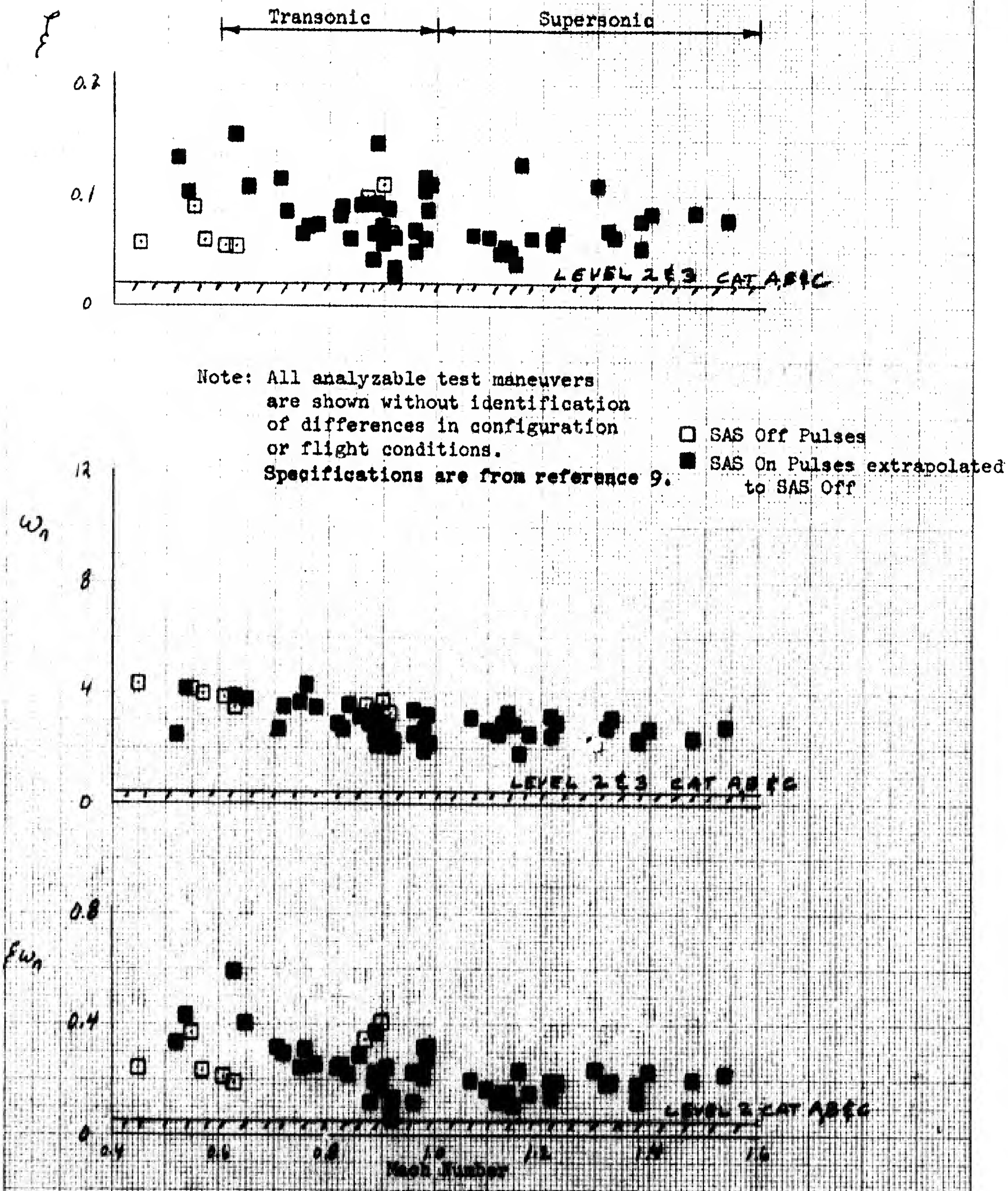


Figure 55. Flight Test Dutch Roll Characteristics
(Transonic and Supersonic - SAS Off)

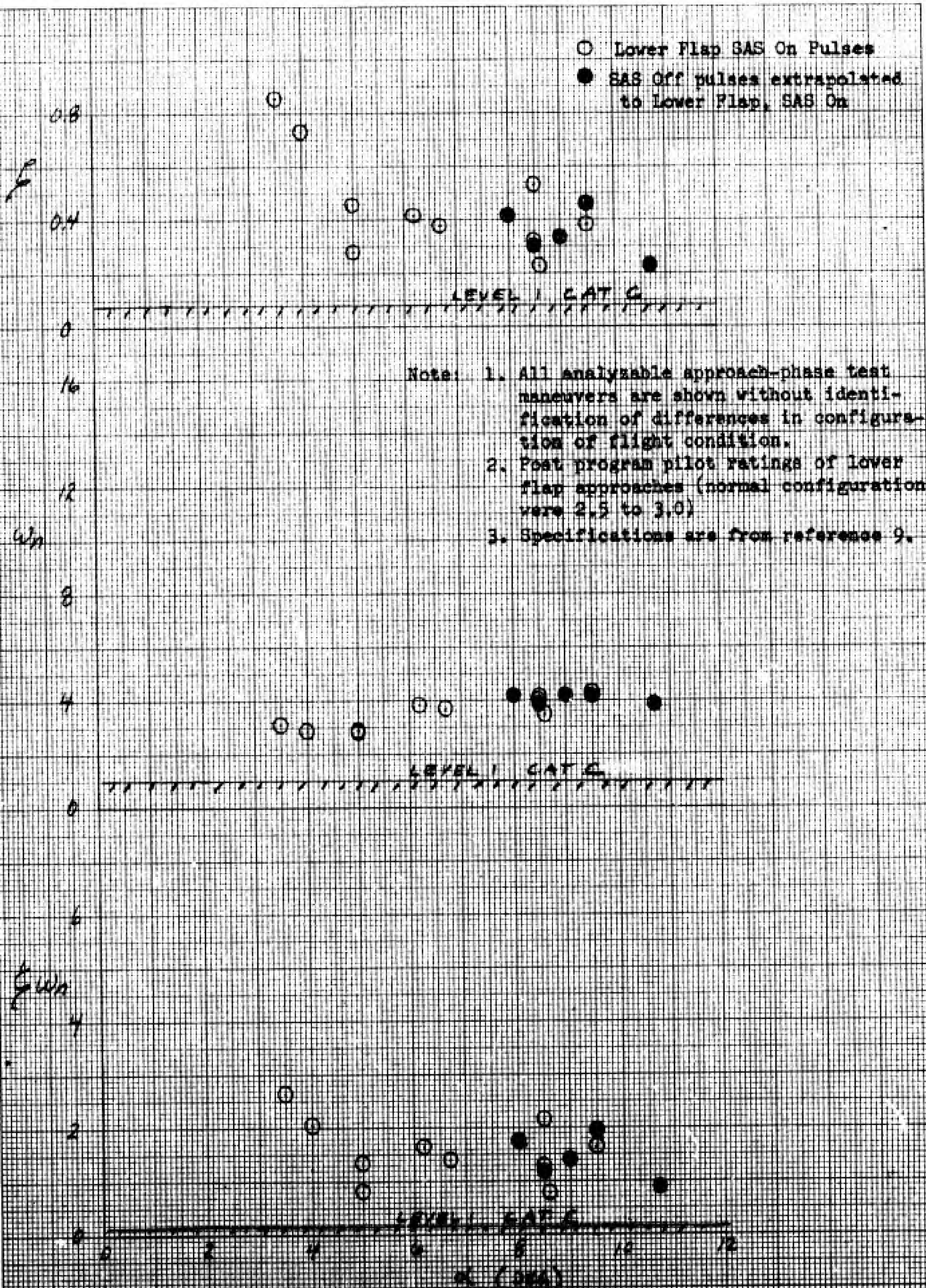


Figure 56. Flight Test Dutch Roll Characteristics (Approach - Lower Flap, SAS On)

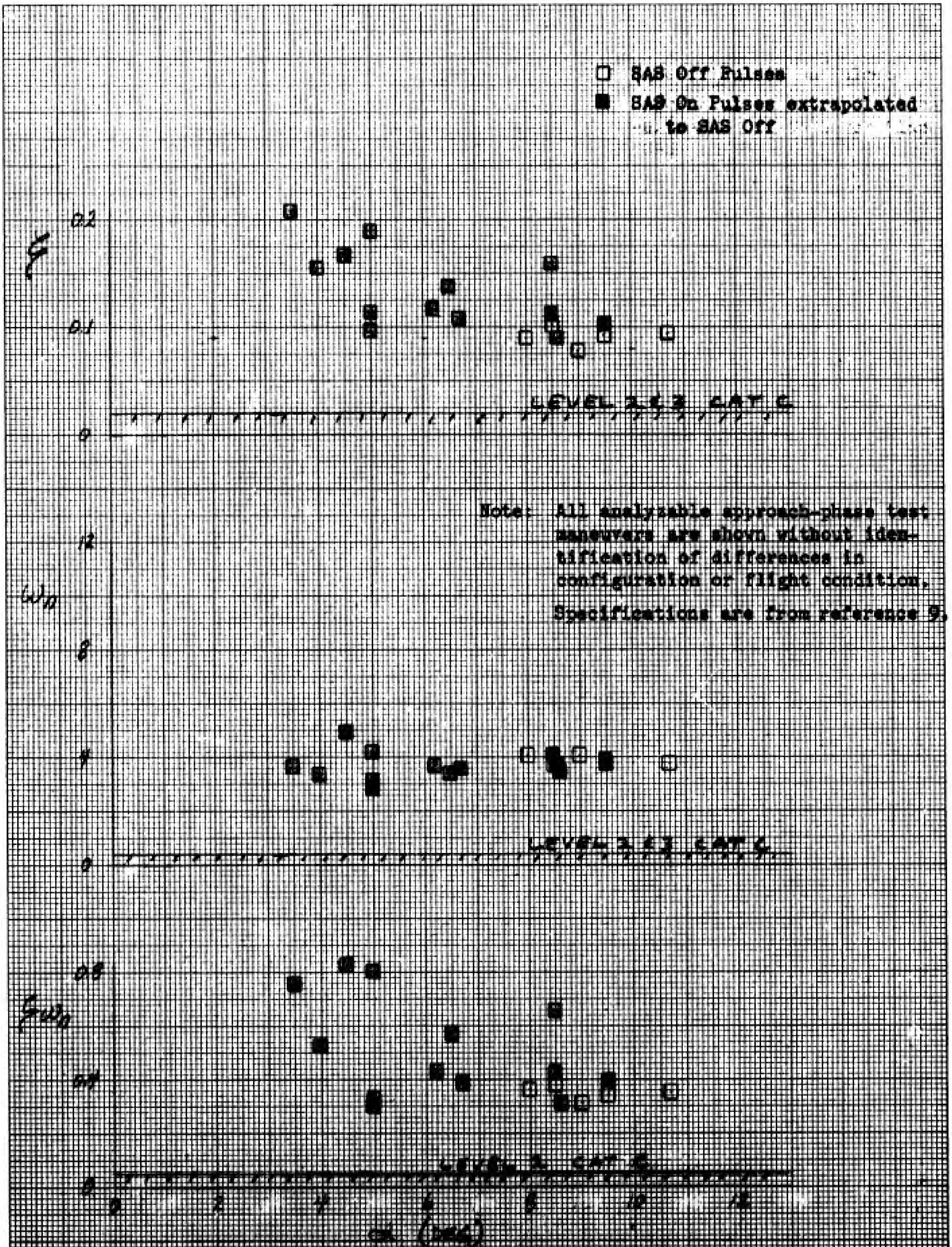


Figure 31. Flight Test Data Roll Characteristics
(Approach - SAS Off)

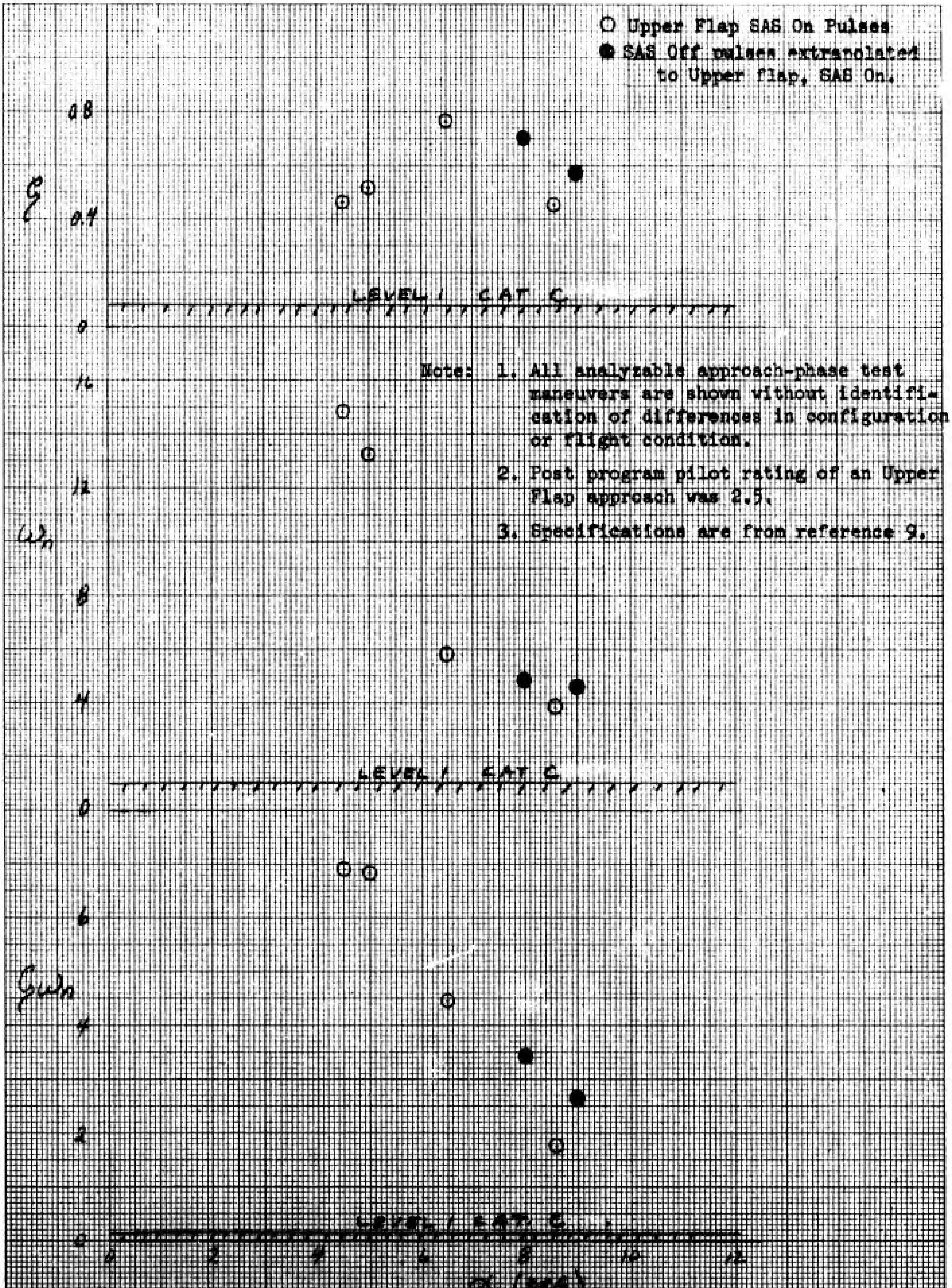


Figure 58. Flight Test Dutch Roll Characteristics
(Approach - Upper Flap, SAS On)

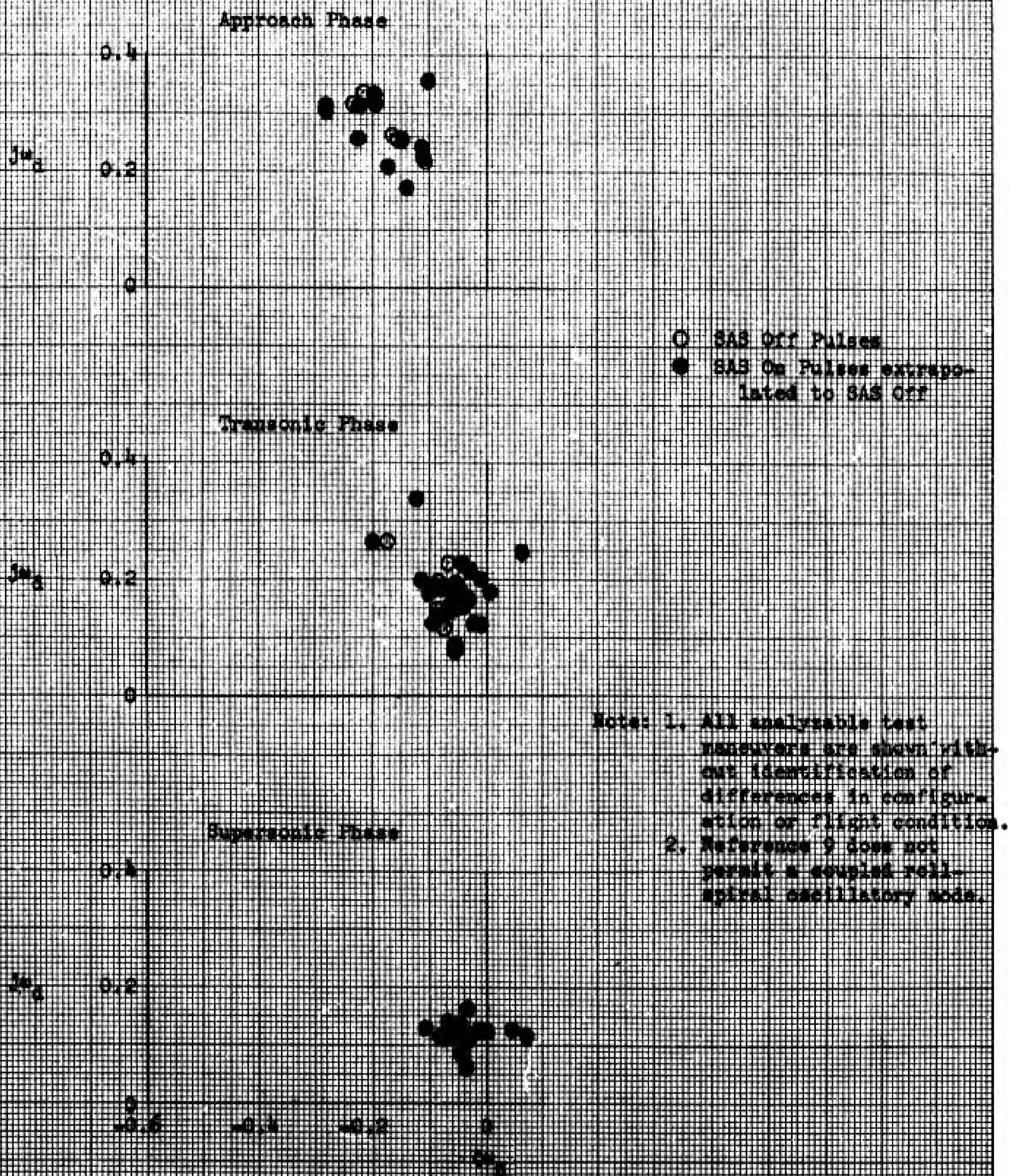
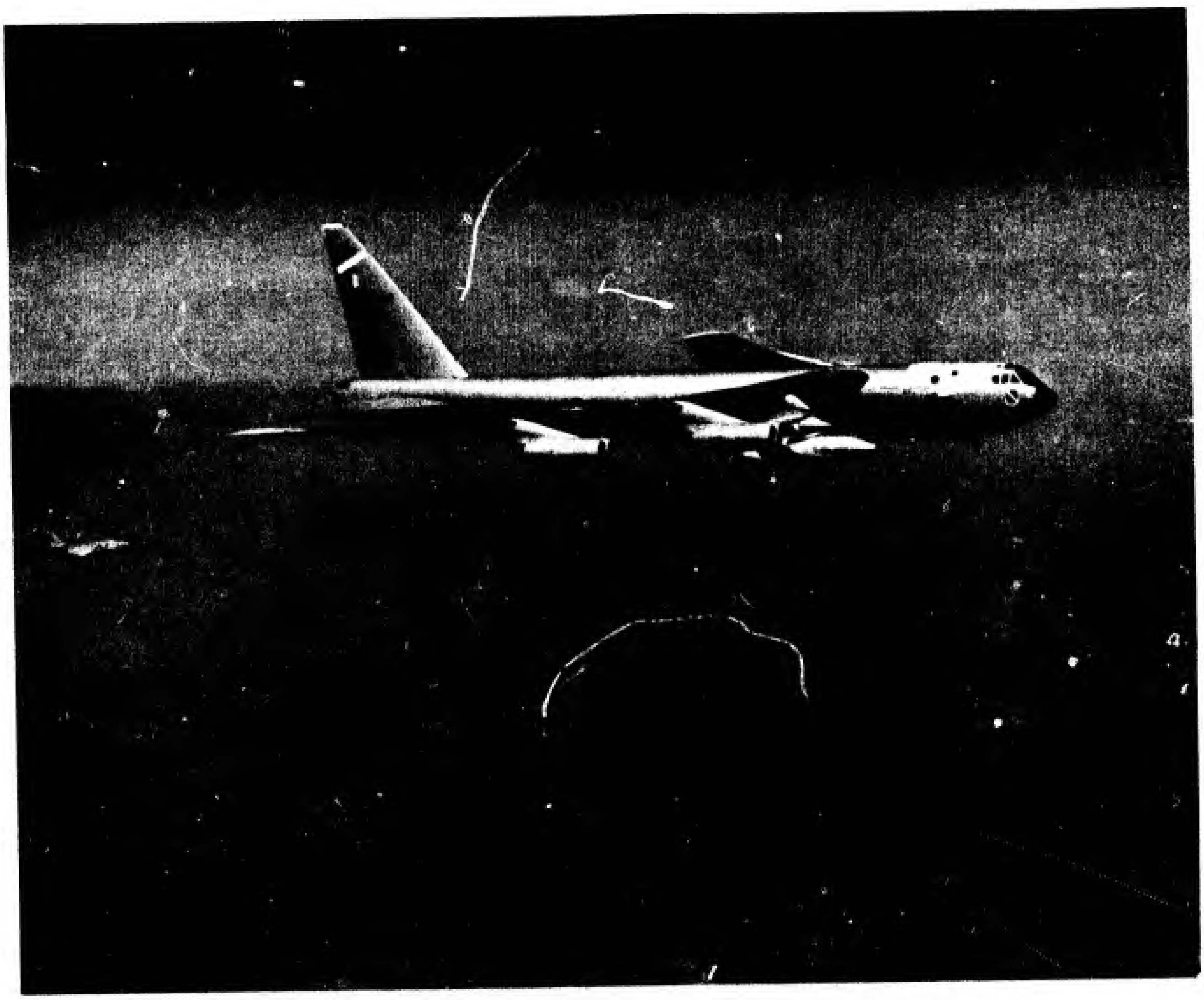


Figure 38: Coupled Roll-Spiral Characteristics - SAS Off

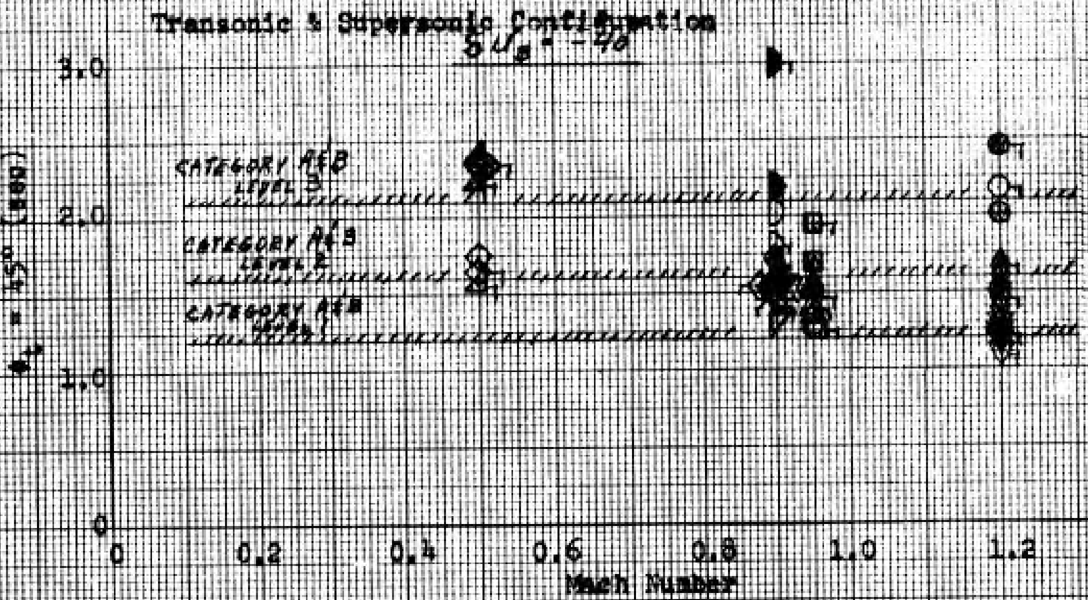
ROLLING PERFORMANCE

The results from the aileron rolls performed on the updated X-24A simulator are shown in figure 60. The rolling performance in the approach configuration met the requirements of reference 9. In the transonic and supersonic flight regime the roll response did not meet the specification requirements with SAS on. The poor pilot ratings shown for the transonic regime, however, resulted from spurious roll inputs and PIO sensitivity, rather than low roll power. The pilots felt that the rolling capability was adequate for all phases of the X-24A mission, except for landing in a crosswind or moderate turbulence. This characteristic of the X-24A with respect to upsets in turbulence emphasized the importance of matching the roll power with the dihedral effect during the design stage. A vehicle with high dihedral effect such as the X-24A must have proportionately higher roll power to control lateral gusts, whereas a vehicle with low dihedral effect would be less affected by the same gust.



Note: 1. Pilot ratings are for SAS On conditions only.
2. Flagged symbols = Right Input
Plain symbols = Left Input
Closed symbols = SAS On
Open symbols = SAS Off
3. Specifications are from reference 9.

Phase	α	Post Program Ratings Pilot B	Pilot C
Supersonic	Low (V=200kts)	2.5	2.5
Supersonic	Low (V=250kts)		
Supersonic	High	2.5	3
Transonic Glide	Low	4	3-5
Transonic Glide	High	3	4
Transonic Pushover	Low	3.5	4
Transonic Boost	Low	3	3
Transonic Boost	High	4.5-5	4
Subsonic	Low		
Subsonic	Mid		
Approach	Low	2.5	3
Landing	Mid		
Landing	High	2.5	3



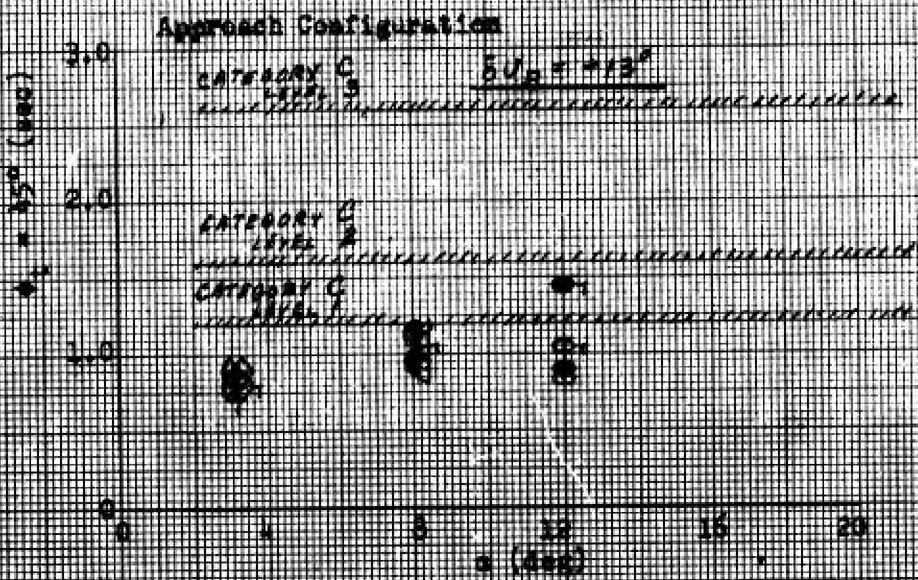


Figure 60. Time-To-Bank Characteristics

LATERAL-DIRECTIONAL DYNAMIC RESPONSE

Step aileron inputs were performed on the simulator and the time history records analyzed according to the procedure outlined in reference 9, paragraph 3.3.2.2.1. The results of these analyses are shown in figure 61 along with post-program pilot ratings of the X-24A at the same flight conditions. (Analysis according to paragraph 3.3.2.2 showed the same trends as shown in figure 61). Note that rather large, but inconsistent, discrepancies often existed between the left and right aileron inputs for values of P_{osc}/P_{ave}. These were apparently the result of small amounts of lateral mistrim and differences in piloting technique on the simulator, even though a great deal of care was taken to obtain consistent and repeatable maneuvers. (Notice that many of the simulated flight conditions were in regions of known PIO sensitivity and data maneuvers were difficult even on the simulator.)

The response from several of the maneuvers was not analyzable under the P_{osc}/P_{ave} criteria because of insufficient oscillatory motions or continually increasing values of roll rate (resulting in part from SAS yaw rate washout). Although some trends are confirmed by comparing the P_{osc}/P_{ave} criteria with pilot ratings, the existence of the strong PIO tendencies, especially with SAS off, are not obvious from the application of this criteria.

STEADY STATE SIDESLIPS

Steady sideslips performed on the simulator are summarized in figure 62. Notice that all flight conditions met the requirements of the specification; however, all sideslips were limited by aileron deflection, rather than rudder deflection. For the transonic and supersonic phases, the sideslips were severely restricted to less than 2 degrees with full aileron and with rudder pedal deflections of less than 1.0 inch.

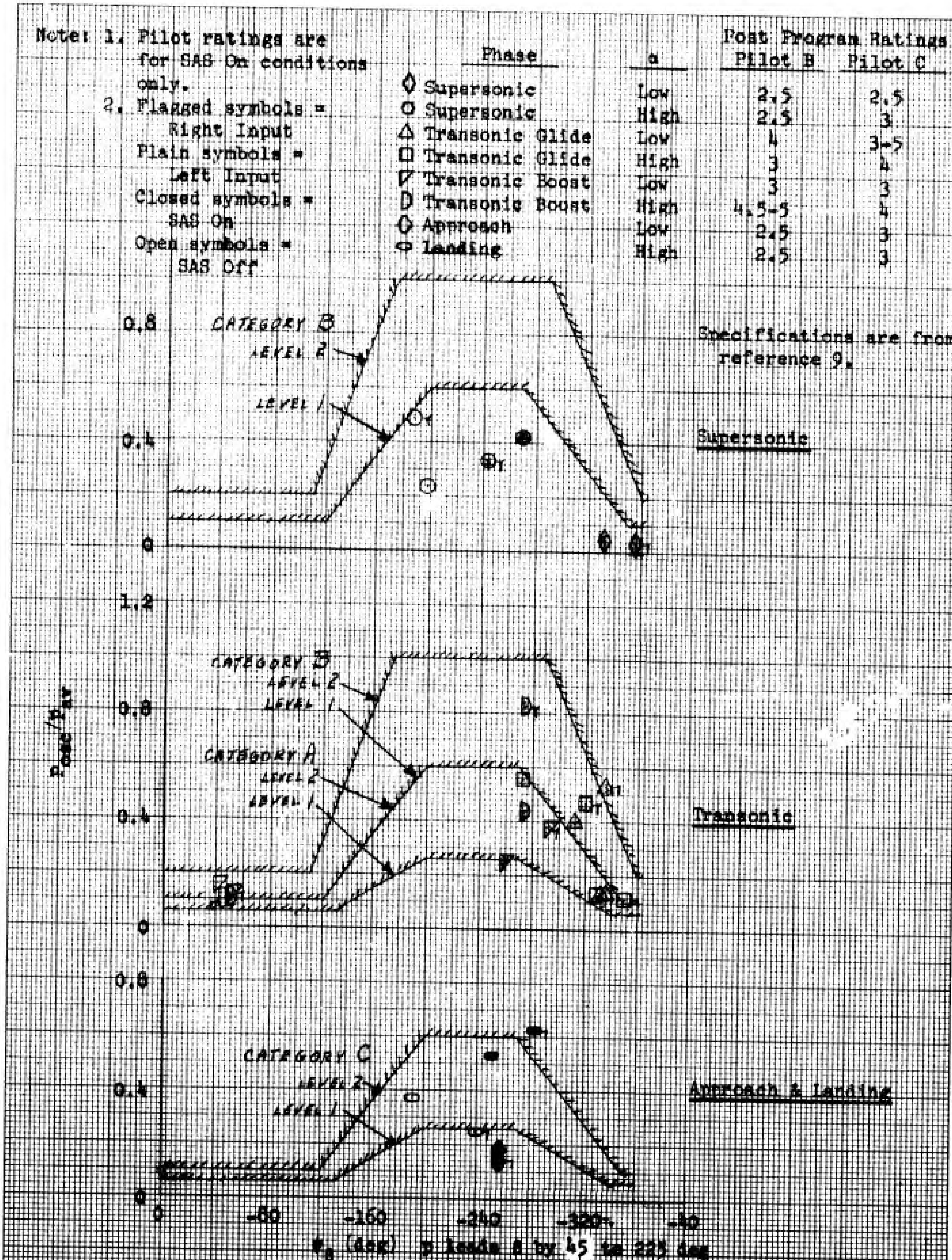


Figure 61. Lateral-Directional Dynamic Response

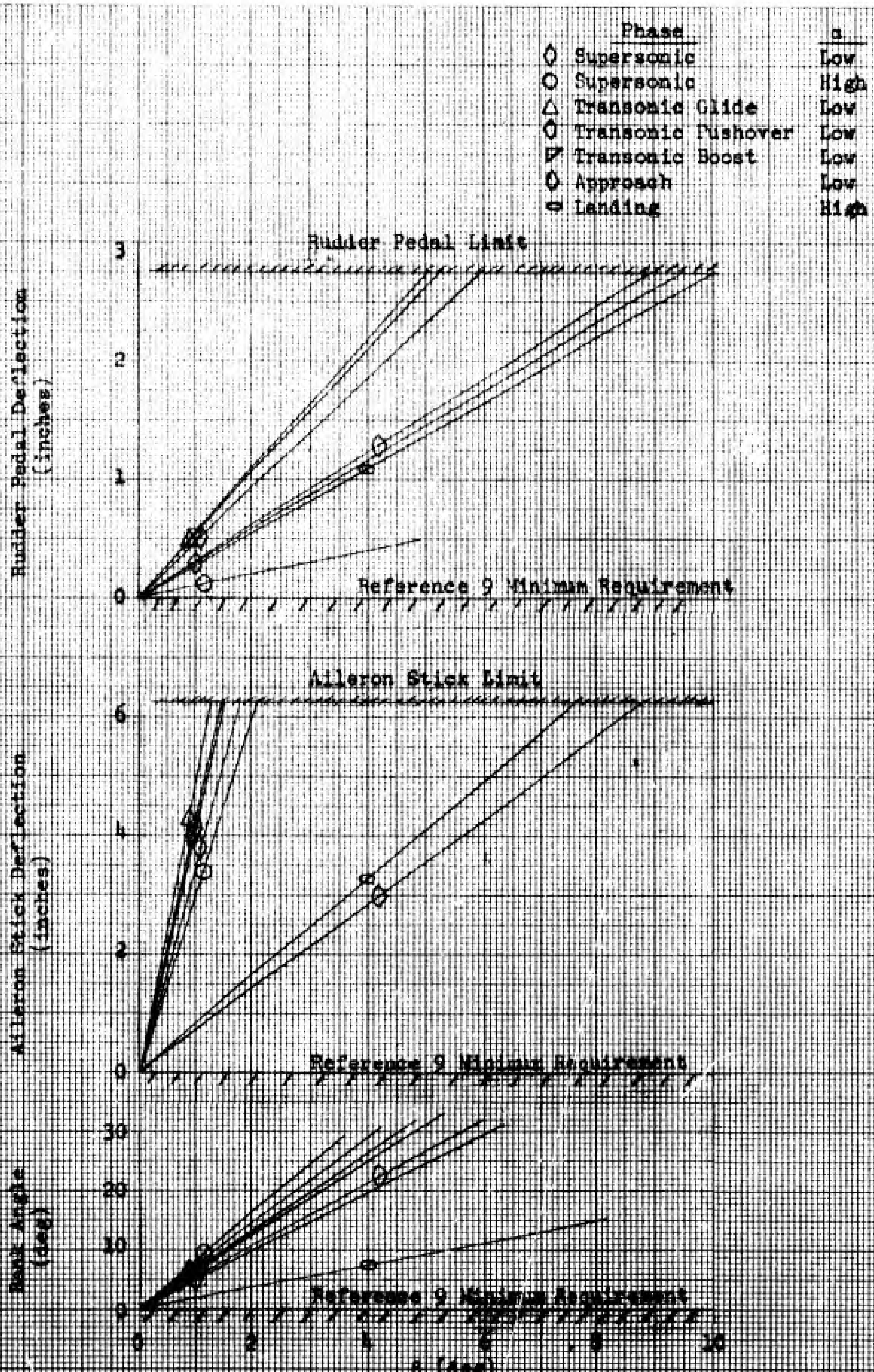


Figure 62. Steady State Sideslip Characteristics

SUMMARY OF COMPARISON WITH PROPOSED SPECIFICATIONS

For those portions of reference 9 which were evaluated, the X-24A generally met the proposed specification. Some handling qualities deficiencies which were uncovered during the flight test program were not identifiable by the application of the proposed specification requirements; namely, a lateral PIO susceptibility in certain flight regimes, and an improper match between low lateral control power and high dihedral effect which caused the vehicle to be marginally controllable during landings in crosswinds or light turbulence.

CONCLUSIONS

The handling qualities of the X-24A were determined through a combination of qualitative pilot comments, numerical pilot ratings, and direct and indirect analyses of recorded flight test data. A fixed-base, six-degree-of-freedom simulator was used extensively to evaluate predicted handling characteristics and to establish trends which were confirmed in flight. The pilots identified different handling characteristics associated with three distinct phases of flight: approach and landing, transonic, and supersonic.

The handling qualities during the approach and landing phase (Mach number less than 0.6) were excellent in still air. The vehicle had an unusually high susceptibility to lateral upsets created by the high dihedral effect and relatively low roll control power. This characteristic resulted in inadequate lateral control capability for landings in crosswinds above 10 knots, as well as small but abrupt rolling motions in light turbulence which were disturbing to the pilot on early flights. Since the X-24A unpowered landing technique required the landing gear to be deployed while close to the ground, the longitudinal trim change associated with landing gear extension was also considered undesirable.

The handling characteristics during the transonic phase (Mach number 0.6 to 1.0) were strongly influenced by the effects of unsteady flow over the tip fins. Flight in this regime was characterized by continual small disturbances, and precise control required a great deal of pilot attention. The combination of low or negative directional stability, low aileron effectiveness, and the use of an aileron-to-rudder interconnect resulted in a strong potential for lateral PIO. Attempts to improve the transonic handling qualities by optimizing the control system features were only partially effective. Although the transonic handling qualities were adequate for a research mission, they would have been marginal for an operational mission due to the difficulty in maintaining precise control.

The supersonic handling qualities were excellent; however, supersonic evaluation time was quite short. Supersonic control power was low in the pitch and roll axes, but the vehicle was stable and had a more solid feel than during the transonic phase.

The rocket engine exhaust plume was found to produce an unpredicted nose-up trim change during the transonic boost phase and a sharp reduction in directional stability at supersonic speeds above 10 degrees angle of attack.

A limited amount of quantitative data from X-24A flight tests and data from post-program simulator tests were compared with criteria specified in reference 9. In most cases the vehicle met the proposed specification. Several of the test maneuvers specified in reference 9 were impractical for a vehicle of this type. The lateral PIO susceptibility of the X-24A and the mismatch between low roll control power and high dihedral effect were not identifiable by application of the proposed specification.

APPENDIX I
TABULATED PILOT RATINGS

X-24A PILOT RATINGS
LAUNCH

Weight[1]	Flight	Pilot	Deg δU_B	Deg δ_L	Deg δR_B	SAS Gain Switch Position[3] K_q	K_p	K_r	KRA[2]	Airspeed KCAS	Mach Number	Altitude 1000 Ft	Pitch Pilot Rating	Roll-Yaw Pilot Rating	Comments
L	1	A	-21	18	-10	3	3	7	A/.5	174	.658	45	3	4.5	58.5% cg
L	2	A	-21	18	-10	3	3	7	M/20	174	.658	45	3.5	4	58.5% cg
L	3	A	-21	18	-10	3	4	7	A/.7	175	.594	40			58.5% cg
L	4	A	-21	18	-10	3	4	7	A/.7	175	.594	40	2	2	58.5% cg, Pilot rating 3 to 5 while trimming
L	5	A	-23	19	-10	3	3	7	A/.7	175	.594	40			57.4% cg
L	6	B	-20	17	-10	3	3	7	A/.7	175	.594	40			57.4% cg
L	7	A	-21	17	-10	3	3	7	A/.7	175	.661	45			considerable lateral mistrim
L	8	A	-30	20	0	3	3	7	A/.7	175	.661	45			
L	9	A	-30	19	0	3	3	7	A/.3	175	.691	47			
H	10	A	-35	20	0	3	3	7	A/.3	175	.594	40	2	2	First heavy weight flight
H	11	B	-35	20	0	3	3	7	A/.3	180	.610	40	2.5	2.5	
H	12	A	-35	21	0	3	3	7	A/.3	185	.625	40	2	2	
H	13	B	-35	21	0	3	3	4	A/.3	185	.653	42			Yaw gain doubled for same switch position
H	14	B	-35	21	0	3	3	4	M/50	185	.653	42	3	3	
H	15	A	-35	21	0	3	3	5	M/50	185	.653	42	2-3	2-3	
H	16	B	-40	26	0	3	3	5	M/50	185	.653	42			
H	17	A	-40	26	0	3	3	5	M/50	185	.653	42			
H	18	B	-40	26	0	3	3	5	M/50	185	.653	42			
H	19	B	-40	26	0	3	4	5	M/50	185	.682	44			
H	20	A	-40	26	0	3	4	5	M/50	185	.696	45			
H	21	B	-40	26	0	3	4	5	M/50	185	.696	45			
L	22	C	-35	24	0	3	4	5	M/50	175	.661	45			
H	23	B	-40	26	0	3	4	5	M/50	185	.696	45			
H	24	C	-40	26	0	3	4	5	M/50	185	.696	45	2.5	2.5	
H	25	B	-40	26	0	3	4	5	M/50	185	.696	45			
H	26	C	-40	25	+2	3	4	5	M/50	185	.696	45	2	2	
H	27	B	-40	25	+2	3	4	5	M/50	190	.744	47			
H	28	B	-40	25	+2	3	4	5	M/50	190	.744	47			
Post Program															
L		B	-40	25	0	3	4	5	M/50	185	.700	45	3.5	2.5	
		C	-40	25	0	3	4	5	M/50	185	.700	45	2	3	
H		B	-40	25	0	3	4	5	M/50	185	.700	45	2.5	2	
		C	-40	25	0	3	4	5	M/50	185	.700	45	3	3	
L		A	-21	18	-10	3	3	7	A/.5	174	.650	45	3	3.5-4	Simulator Pilot ratings

[1] H=Heavy Weight (11,000 to 11,500 lb)
L=Light Weight (6,300 to 6,700 lb)

[2] A=Auto/Mach Repeater Setting
M=Manual/KRA Setting

[3] The relationship between switch position and actual SAS gain is discussed in Reference 4.

X-24A PILOT RATINGS
TRANSONIC BOOST PHASE

Flight	Pilot	Deg δU_B	Deg δR_B	SAS Gain Switch Position K_q	K_p	K_r	KRA[1]	Chambers On (See Fig 2)	Mach Number	Airspeed KCAS	Task	Pitch Pilot Rating	Roll-Yaw Pilot Rating	Comments
10	A	-35	0	3	3	7	A/.3	2,3,4	.6-.75	175-260	α,ϕ	3	3	17°α
									.7	250-220	θ	2		13°-14°α
11	B	-35	0	3-5	3	7	A/.3	1,2,3,4	.7		α	4		No noticeable effect from gain change (pilot rating based on engine trim change)
									.7-.75	<253	ϕ		2.5-4	Spurious lateral inputs rated 4.0
12	A	-35	0	3	3	7	A/.3	All	.8-.85	<277	θ	3-3.5		
13	B	-35	0	3	3	4	A/.3	1,4	.65-.75	180-240				
14	B	-35	0	3-5	3	4	A/.3	All	.8-.86	200-260	α,ϕ	3	3	17°α
									.85-.95		θ,ϕ	2.5-3*	2.5-3*	10°-14°α
15	A	-35,-40	0	5	3	5	A/1.1	All	.85-.9	260-230	α,ϕ	4-5	2-3	Pitch pilot rating 17°α
								2,3,4	.86-.9	230-175	ϕ		4	Low q after shutting down #1 and 15°α at .95
								2,4	.9-.95	175-190			3	12°-14°α stabilized
16	B	-40	0	5	5	5	A/1.1	All	.8-.9	255-220	α,ϕ	2.5*	2.5*	Tight ϕ control ∼11°α, flew better in pitch
								1,2,4	.92-.94	220-175	ϕ		3.0	After shutting down #3 at 13°α
17	A	-40	0				A/1.1	1,3						
18	B	-40	0	5	5	5	A/1.1	All	.65-.78	200-250	α	3.5*		Good evaluation at 17°α
									.9-.95	190-200	α5°		4.0*	Pushover got worse
19	B	-40	0	5	5	7	A/1.1	All	.8-.88	220-172	θ	3.0		11°-13°α
									.98-1.17	172-220	α7°		2.5	Mostly supersonic
20	A	-40	0	5	4	5	A/1.1	All	.8-.88	200-170	θ	3		4.0 for trim changes at peak q (11°-13°α)
									.82	177	ϕ∼15°α		7.0	Pushover got better (due to Mach > 1.0)
21	B	-40	0	5	4	5	A/1.1	All,2						
23	B	-40	0	5	4	5	A/1.1	All	.85-1.0	169-200	ϕ		4.5	Low q area, 13°-10°α
24	C	-40	0	5	4	5	A/1.1	1,2,4	.7-.85	[illegible]0-250	α17°	4.0		May be turbulence
									.8	2[illegible]0	θ	2.0		14°-16°α
25	B	-40	+2	5	4	5	A/1.1	All	.8-.95	17[illegible]	ϕ		4.5-5*	Low q 13°-10°α
26	C	-40	+2	5	4	5	A/1.1	All	.7-.8	215-275	α-θ	2.0		
									.8-.95	190-200	ϕ		4	10°α
Post Program														
	B	-40	0,+2	5	4	5	A/1.1	All		200-260	high α	3.5	3	
										150-200	high α	4	4.5-5	
											Pushover	3.5	3.5	
	C	-40	0,+2	5	4	5	A/1.1	All		200-260	high α	2	3	
										150-200	high α	3.5	4	
											Pushover	2.5	4	

[1]A = Auto/Mach repeater setting
M = Manual/KRA setting

*Specific handling qualities task evaluation

X-24A PILOT RATINGS
SUPERSONIC PHASE

Flight	Pilot	Deg δU_B	Deg δR_B	SAS Gain Switch Position K_q	K_p	K_r	KRA[1]	Chambers On	Mach Number	Airspeed KCAS	Task	Pitch Pilot Rating	Roll-Yaw Pilot Rating
18	B	-40	0	5	5	5	A/1.1	All	1.0-1.18	200	ϕ,10°α	2	2
19	B	-40	0	5	5	7	A/1.1	1,2,4	∼1.1	200-230	12°α		2.5
20	A	-40	0	5	4	5	A/1.1	All	1.0+	200	ϕ@7°α		3.0
26	C	-40	+2	5	4	5	A/1.1	All	∼1.3	200-230	12°α		5.0
Post Program													
	B	-40	0,+2	5	4	5	A/1.1	All			low α	2.5	2.5
											high α	2.5	2.5
	C	-40	0,+2	5	4	5	A/1.1	All			low α	2	2.5
											high α	2	3

[1]A = Auto/Mach repeater setting
M = Manual/KRA setting

X-24A PILOT RATINGS
TRANSONIC GLIDE PHASE

Flight	Pilot	Deg δU_B	Deg δR_B	SAS Gain Switch Position K_q	K_p	K_r	KRA[1]	α for zero Percent KRA	Mach Number	Airspeed KCAS	α	Task	Pitch Pilot Rating	Roll-Yaw Pilot Rating	Comments
1	A	-21	-10	3	3	5	M/35	0°	.5	∼200	∼8°	Turn	2.5	3-3.5	
2	A	-21	-10	3	4	3	A/.7	0°	.5	∼200	∼8°	Turn	2.0	2.5	
3	A	-21	-10	3	0	0	A/.7	6°							
4	A	-21	-10	3	0	0	A/.7	6°	.6	∼200	∼11°	Lat-Eval		4.5-5.0	
5	A	-21	-10	3	3	7	A/.7	6°	.5-.6	∼200	10-12°	Overall		4.5-5.0	Lat Trim Change
6															
7	A	-30	-10,0	3	2	7	A/.7	6°	.5-.6	∼200	10°	Pushover-Pullup	2-3	5	Lat Mistrim
8	A	-30	0	3	2	7	A/.7	6°	.7	∼220	3-15°	Pushover-Pullup	3	4	
9	A	-30	0	3	2	7	A/.7	6°	.7-.5		12°	Decel	3	3	
10	A	-35	0	3	3	7	A/.3	3°	.8-.65	235-180	7°	Decel			
11	B	-35	0	3	0	0	A/.3	3°	.75-.8	∼160	5,10,15°	Lat-Eval		4	Uncomfortable Pulses Only
12	A	-35	0	3	0	0	A/.3	3°	.8-.85	170-210	7°	Lat-Eval		5*	Better at 15° than 5° & 10°
13	B														Good SAS Off Eval
14	B	-35	0	5	0	0	A/.3	0°	.9	170+	5°	Lat-Eval		6.5	
15	A	-40	0	5	5	5		0°	.9	170+	5°	Lat-Eval		2.5	
16	B	-40	0	5	5	5	A/1.1	0°	.97	170+	5°	Lat-Eval		3.0	
19	B	-40	0	5	4	7	A/1.1	0°	.9-.98	210	4°	Lat-Eval		4.0	
23	B	-40	0	5	4	5	A/1.1	0°	.9	190	14°	Lat-Eval		3.0	
25	B	-40	+1	5	0	5	A/1.1	0°	.6	230	12°	Lat-Eval		3.0	
				5	0	0	A/1.1	0°	.6	250	10-12°	Lat-Eval		8-9*	First Time
26	C	-40	+2	5	4	5	A/.3	0°	.65	230	5-7°	Lat-Eval		6.5*	Second Time
														5	Low KRA Slope
Post Program															
	B	-40	0,+2	5	4	5	A/1.1		.6-1.0	---	Low	α,ϕ	3	4	
											High		3	3	
	C	-40	0,+2	5	4	5	A/1.1		.6-1.0	---	Low	α,ϕ	2	3	
											High		3	4	
											Very Low		2	5	

[1]A = Auto/Mach repeater setting
M = Manual/KRA setting

*Specific handling qualities task evaluation

X-24A PILOT RATINGS
CONFIGURATION CHANGE

Flight	Pilot	Deg δ_{UB} Start, End	Deg δ_{RB} Start, End	K_q	K_p	K_r	Mach Number Start	Pitch Pilot Rating	Roll-Yaw Pilot Rating	Comments
5	A	-23,-10	--	3			.48	3		
6	B									
7	A		0-10	3	2	7	.59	3		
8	A	-30,-15	0-10	3	2	7	.52	2	2	Separate δ_{UB}, δ_{RB}
9	A	-35,-15	0-10	3	2	7	.48	2-3*	2-3*	Combined δ_{UB}, δ_{RB}
10	A	-35,-13	0-10	3	2	7	.47			Hands Off
11	B	-35,-13	0-10	3	2	7	.5	3	3	
12	A	-35,-13	0-10	3	3	7	.52			
13	B	-35,-13	-10	3	2	4	.5		4	Lat PIO
14	B	-35,-13	0-10	3	2	4	.485	2.5		Lat PIO
15	A	-40,-13	0-10	3	2	5	.48			PIO Tendency Noted
16	B	-40,-13	0-10	3	2	5	.44			Like Simul., PIO Again Slight
17	A	-40,-13	0-10							
18	B	-40,-13	0-10	3	2	5	.46			No Task--No PIO--Visibility Out Window Prime
19	B	-40,-3	0-10	4	3	5	.42			Better Than Simul
23	B	-40,-13	0-10	3	2	5	.45			No PIO Tendency
24	C	-40,-13	0-10	3	2	5	.41	2.5	2.5	
25	B	-40,	+2	3	0	0	.44		6-6.5*	Dampers Off
		-13	-10		0	0			3.5*	Dampers Off
Post Program										
	B	-40,-13	0-10	3	2	5	.5	3.5	3.0	
	C	-40,-13	0-10	3	2	5	.5	2.5	3.0	

*Specific handling qualities task evaluation

X-24A PILOT RATINGS
APPROACH PHASE

Flight	Pilot	Airspeed	Deg δU_B	Deg δR_B	δ_L	SAS Gain Switch Position K_q	K_p	K_r	KRA (% Indicated)	KRA[1]	Pitch Pilot Rating	Roll-Yaw Pilot Rating	Riding Quality	Comments
1	A	270	-21	-10	20	3	3	7	35	M	3	4-5		KRA malfunction. (Simulator ratings 3,3)
2	A	270	-21	-10	19	3	4	3	10-15	A	2.5	6-7		KRA 0°α intercept-40% stop
3	A	260	-21	-10	21	3	4	6	0	A		5-6		KRA 6°α intercept - higher surface rates - roll stick force gradient and damping increased
4	A	290	-21	-10	20	3	4	6	0	A		3-3.5	5*	
5	A	270	-18	-10	15	3	3	7	0	A		3-3.5*	5	
6	B	300	-22	-10	21	3	2	7	0	A	3	3*	4	
7	A	285	-12	-10	4	3	2	7	0	A		3.5-4		Increased pitch force gradient and 15% gearing reduction
8	A	290	-15	-10	9	3	2	7	0	A				
9	A		-13	-10	7					A				
10	A		-13	-10	6	3	2	7	0	A				
11	B		-13	-10	7	3	2	7	0	A	2	2	2-2.5	KRA 50% stop
12	A		-13	-10	7	3	2	7	0	A	2	2		
13	B		-13	-10	7	3	2	4	0-10	A				KRA 0°α intercept, 15% pitch gearing increased, pitch breakout +.5#, yaw gain doubled
14	B		-13	-10	7	3	2	5	0-10	A				
15	A		-13	-10	5				0-10	A	2.5-3			
16	B		-13	-10	7	3	2	5	50	M				Roll force breakout +1.0#
17	A		-13	-10	7	3	2	5	0-10	A				
18	B	270	-13	-10	7	3	2	5	0-10	A				
19	B		CONTR	-10	0	4	3	5	0-10	A	2	2.5	2.5	Upper flap approach
20	A		CONTR	-10	0	4	2	5	0-10	A	2*	2*	2*	Upper flap approach
21	B		-13	-10	7	3	2	5	0-10	A				
22	C		-13	-10	7	3	2	5	0-10	A				
23	B		-13	-10	7	3	2	5	0-10	A				
24	C		-13	-10	7	3	2	5	0-10	A			3	
25	B		-13	-10	7	3	2	5	0-10	A				
26	C		-13	-10	7	3	2	5	0-10	A				
27	B		-13	-10	7	3	2	5	0-10	A				
28	B		-13	-10	7	3	2	5	0-10	A				
Post Program														
	B		-13	-10		3	2	5	0-10	A	2	2.5	3.0	
	C		-13	-10		3	2	5	0-10	A	2	3	4	

[1] M = Manual
A = Automatic

*Specific handling qualities task evaluation

X-24A PILOT RATINGS
FLARE AND LANDING PHASE

Flight	Pilot	Deg δU_B	SAS Gain Switch Position K_q	K_p	K_r	Pitch Pilot Rating Gear Transient	Pitch Pilot Rating	Roll-Yaw Pilot Rating	Comments
1	A	-21	3	3	7	4	3	4-5	Simul, ratings 5, 3.5,4.5
2	A	-21	3	4	3	3	2	4	
3	A	-21	3	4	6				
4	A	-21	3	4	6	2.5-3	2.5-3	2.5-3	
5	A	-23	3	3	7	3			
6	B	-22	3	2	7		2	3	
7	A	-19	3	2	7	4			
8	A	-13	3	2	7				
9	A	-13							New nose gear door
10	A	-13	3	2	7	3			
11	B	-13	3	2	7	5			
12	A	-13		2	7				
13	B	-13	3	2	4	3			
14	B	-13	3	2	5				
15	A	-13	3			2.5-3	2.5-3	2.5-3	
16	B	-13	3	2	5				
17	A	-13	3	2	5				
18	B	-13	3	2	5				
19	B	CONTR	4	3	5	--	8	8	Doesn't remember gear transient. Severe cross-wind
20	A	CONTR	4	2	5				Doesn't remember gear transient.
21	B	-13	3	2	5		2-2.5	2-2.5	
22	C	-13	3	2	5				
23	B	-13	3	2	5				
24	C	-13	3	2	5	4	4	4	Crosswind
25	B	-13		2	5				
26	C	-13		2	5				
27	B	-13		2	5				
28	B	-13		2	5				
Post Program									
	B	-13	3	2	5	3.5-6.5	3	2.5	10KT crosswind-lateral-directional pilot rating 8. 6.5 pilot rating for first flight.
	C	-13	3	2	5	4	2.5	3	10KT crosswind-lateral-directional pilot rating 6.

APPENDIX II
FAIRED FLIGHT TEST STABILITY DERIVATIVES

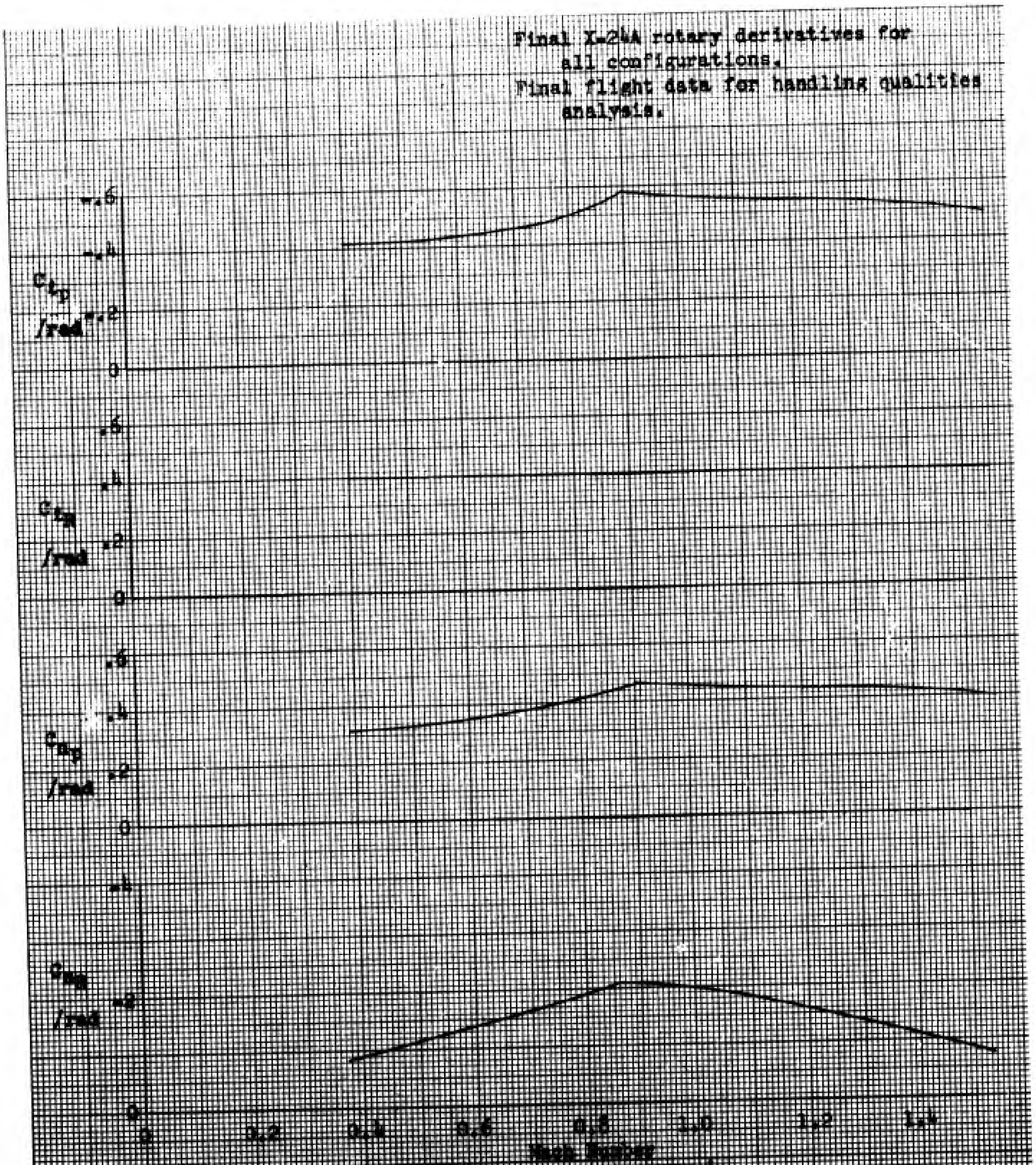


Figure 61. Faired Flight Test Stability Derivatives

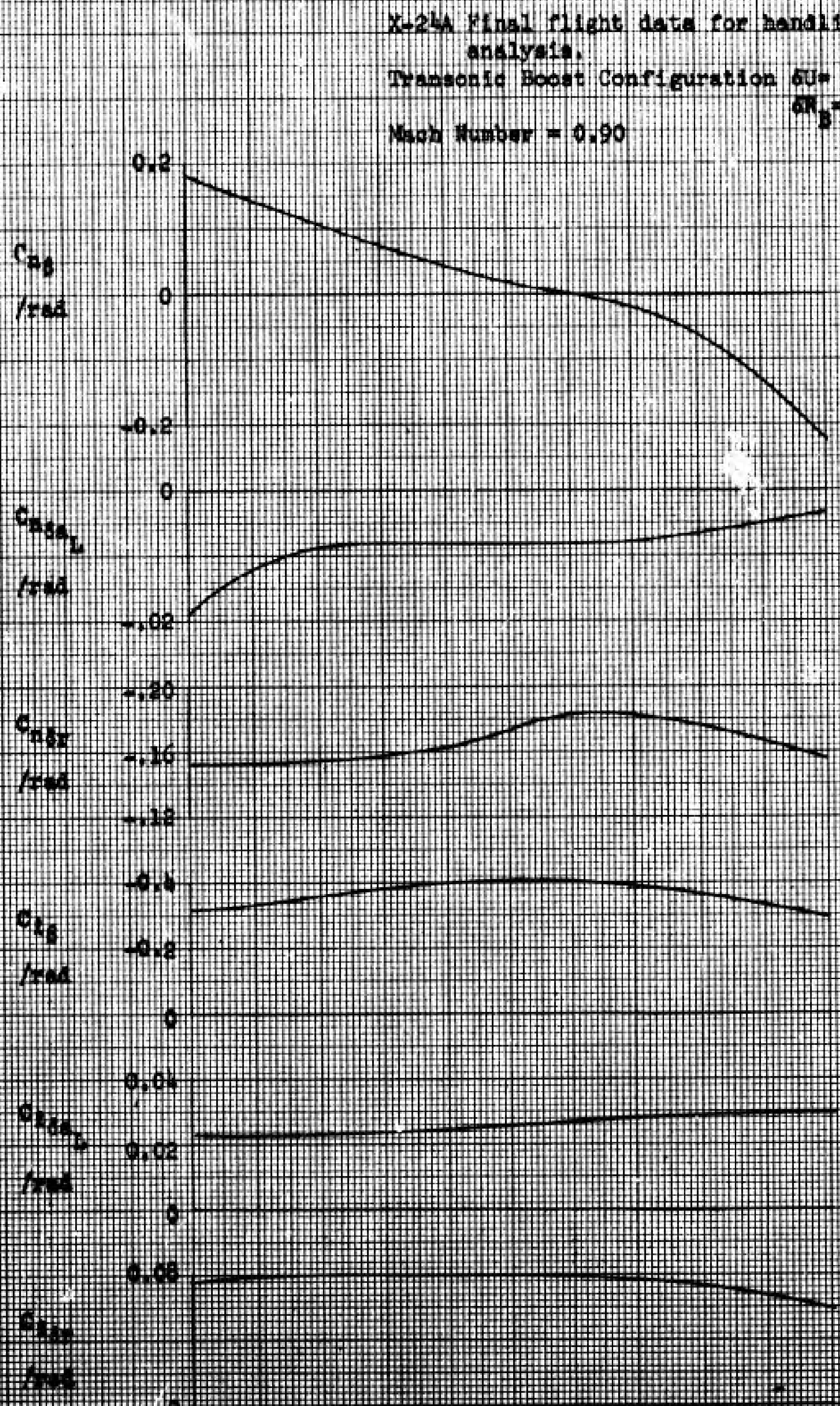


Figure 61. Faired Flight Test Stability Derivatives

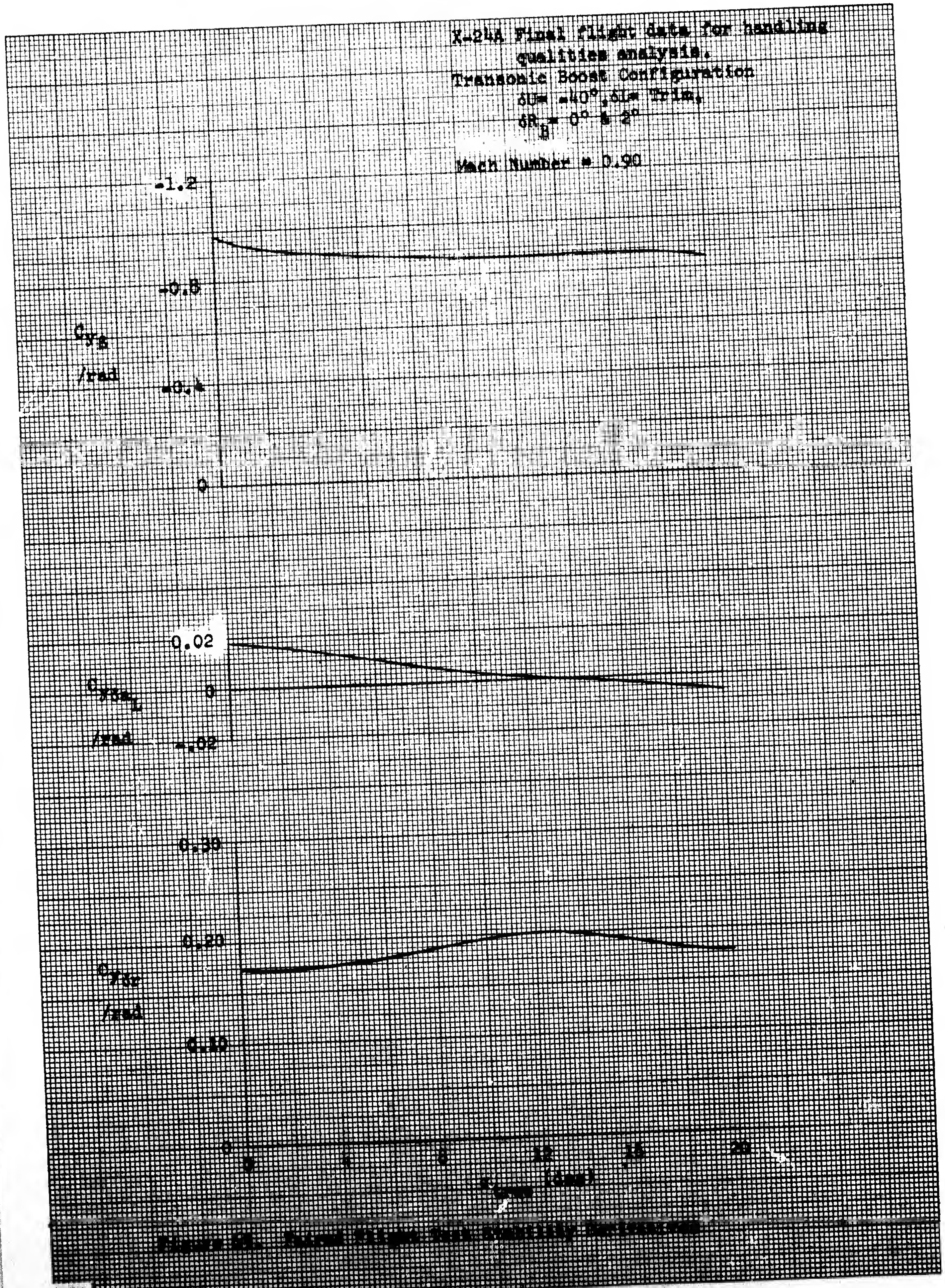


Figure [illegible]. Final Flight Data Stability Derivatives

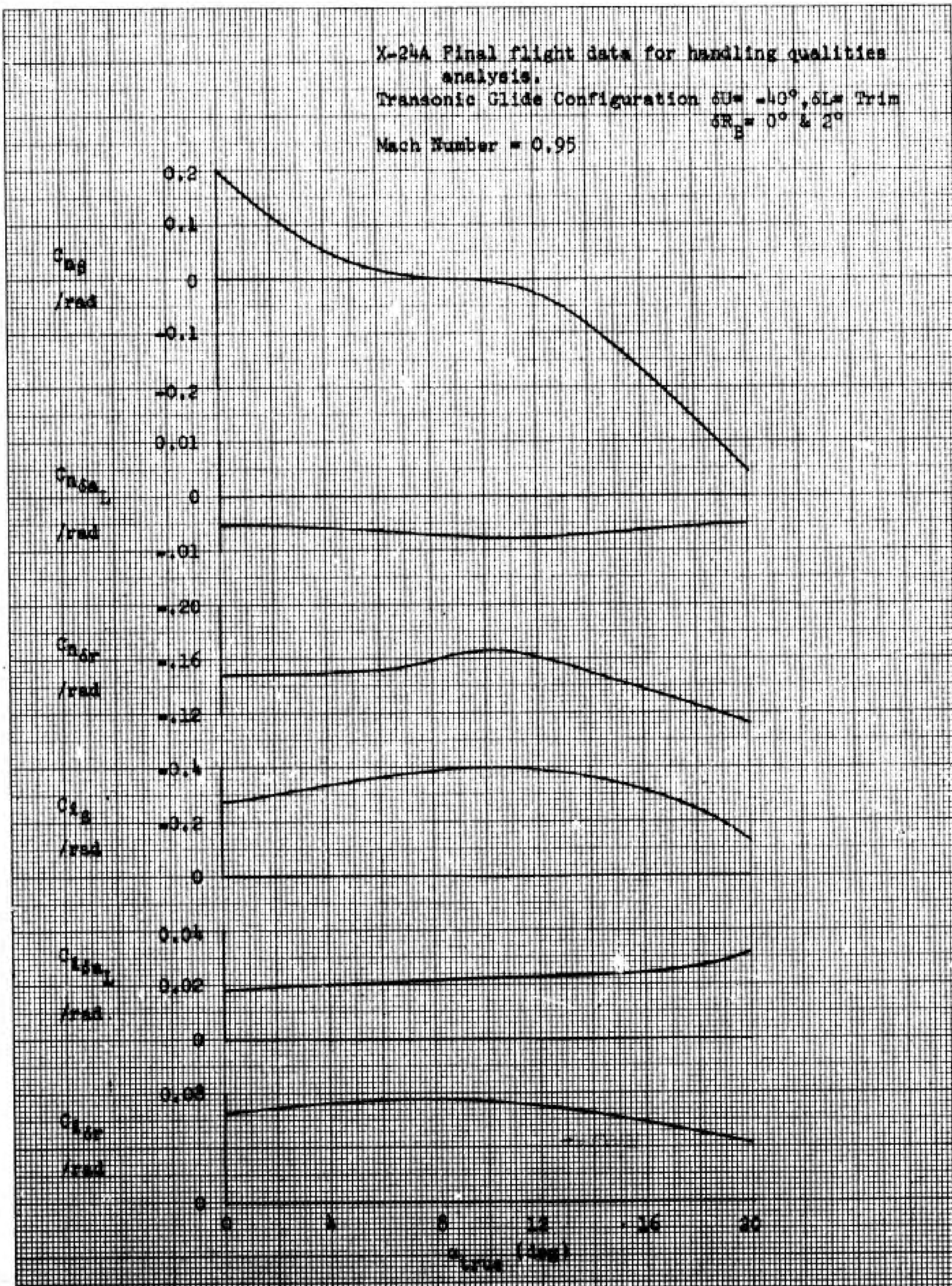


Figure 66. Faired Flight Test Stability Derivatives

X-24A Final Flight Data for Handling Qualities Analysis

Transonic Glide Configuration $\delta U = -40°$, $\delta L =$ Trim, $\delta R_B = 0°$ & $2°$

Mach Number = .95

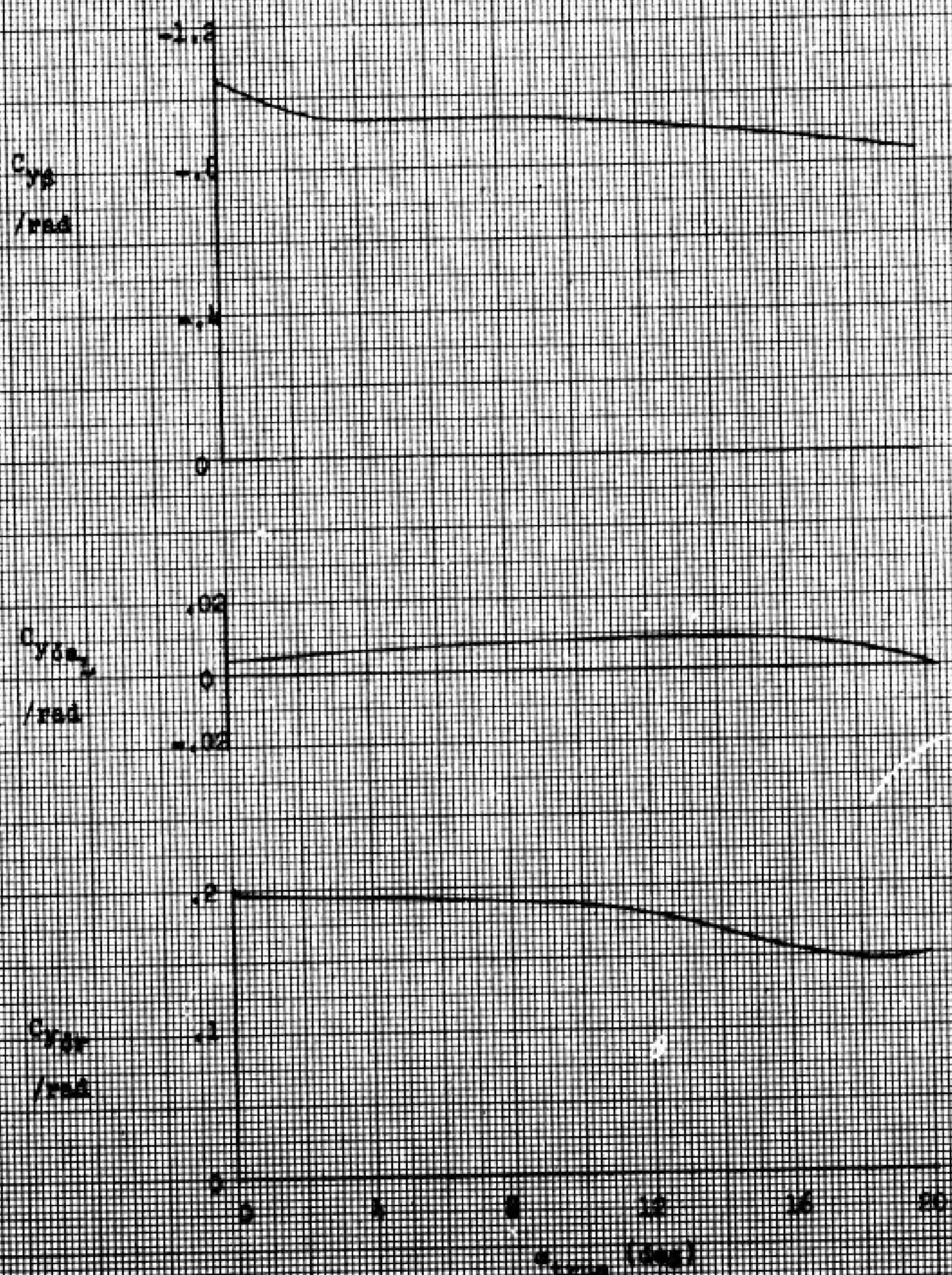


Figure 61. Faired Flight Test Stability Derivatives

X-24A Final flight data for handling qualities analysis.
Supersonic Configuration $\delta U = -40°$, $\delta L =$ Trim
$\delta R_B = 0°$ & $2°$

Mach Number = 1.2

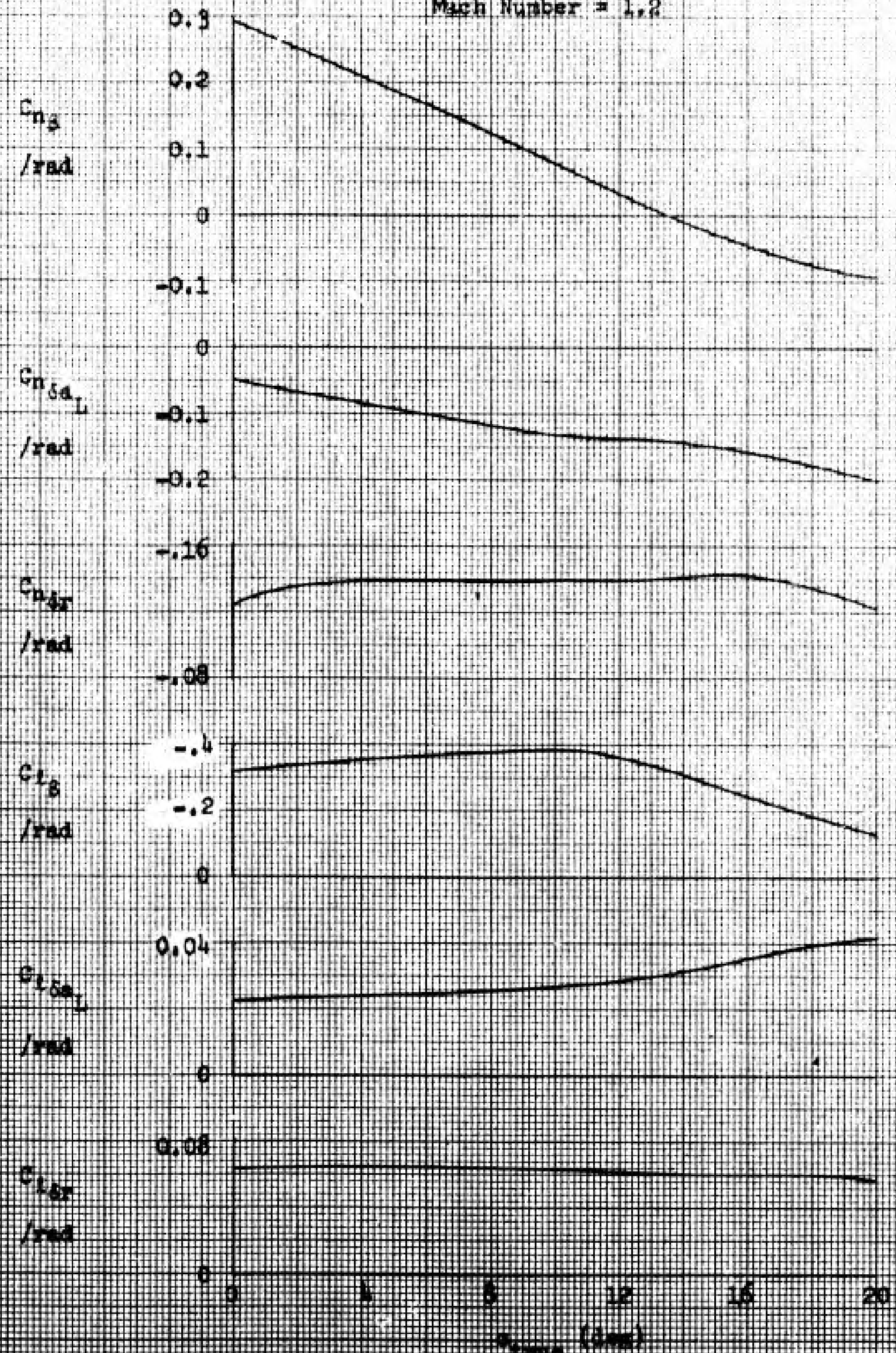


Figure 68. Faired Flight Test Stability Derivatives

X-24A Final flight data for handling qualities analysis.

Supersonic Configuration $\delta U = -40°, \delta L =$ Trim
$\delta R_B = 0° \ \& \ 2°$

Mach Number = 1.2

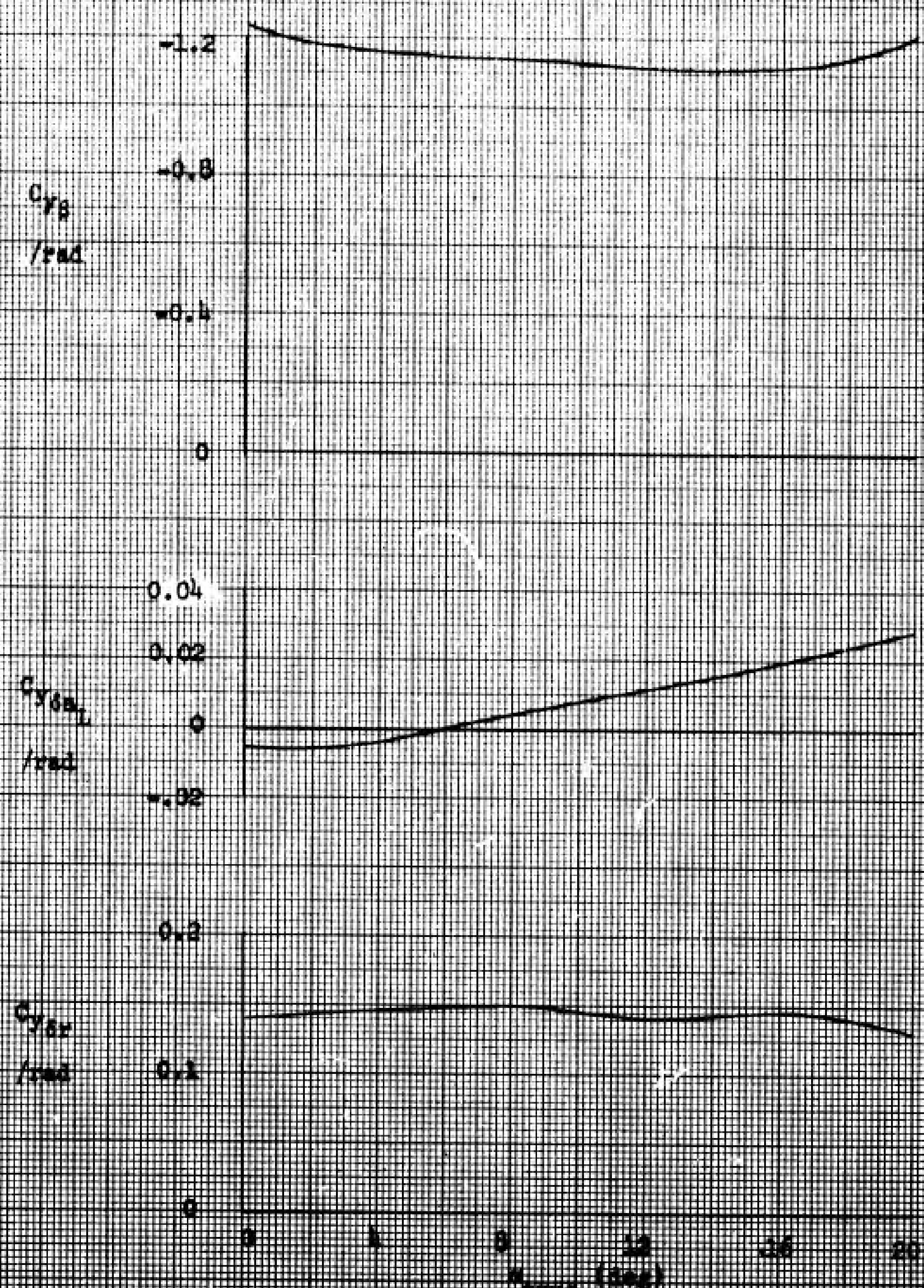


Figure 59. Faired Flight Test Stability Derivatives

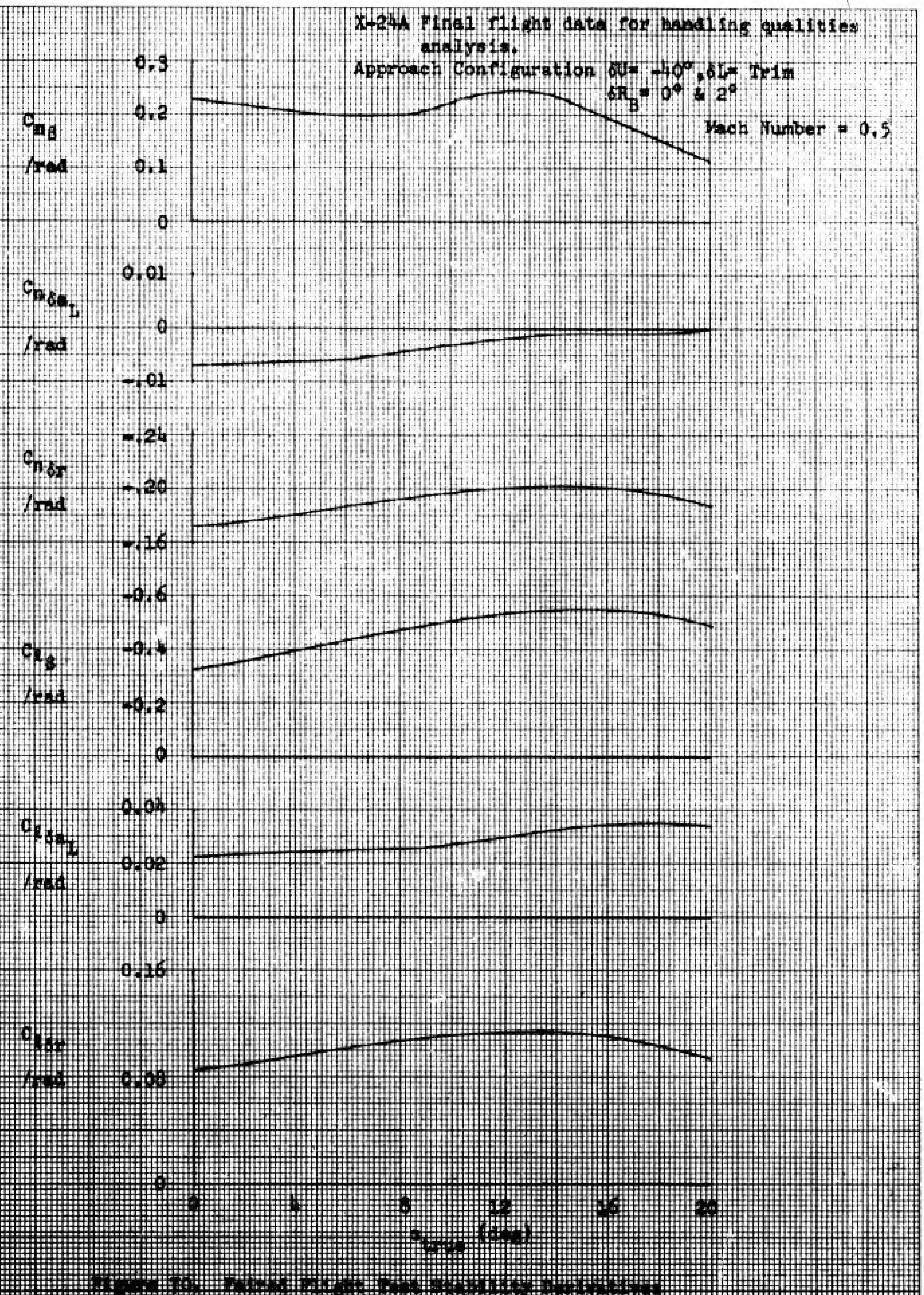


Figure 70. Faired Flight Test Stability Derivatives

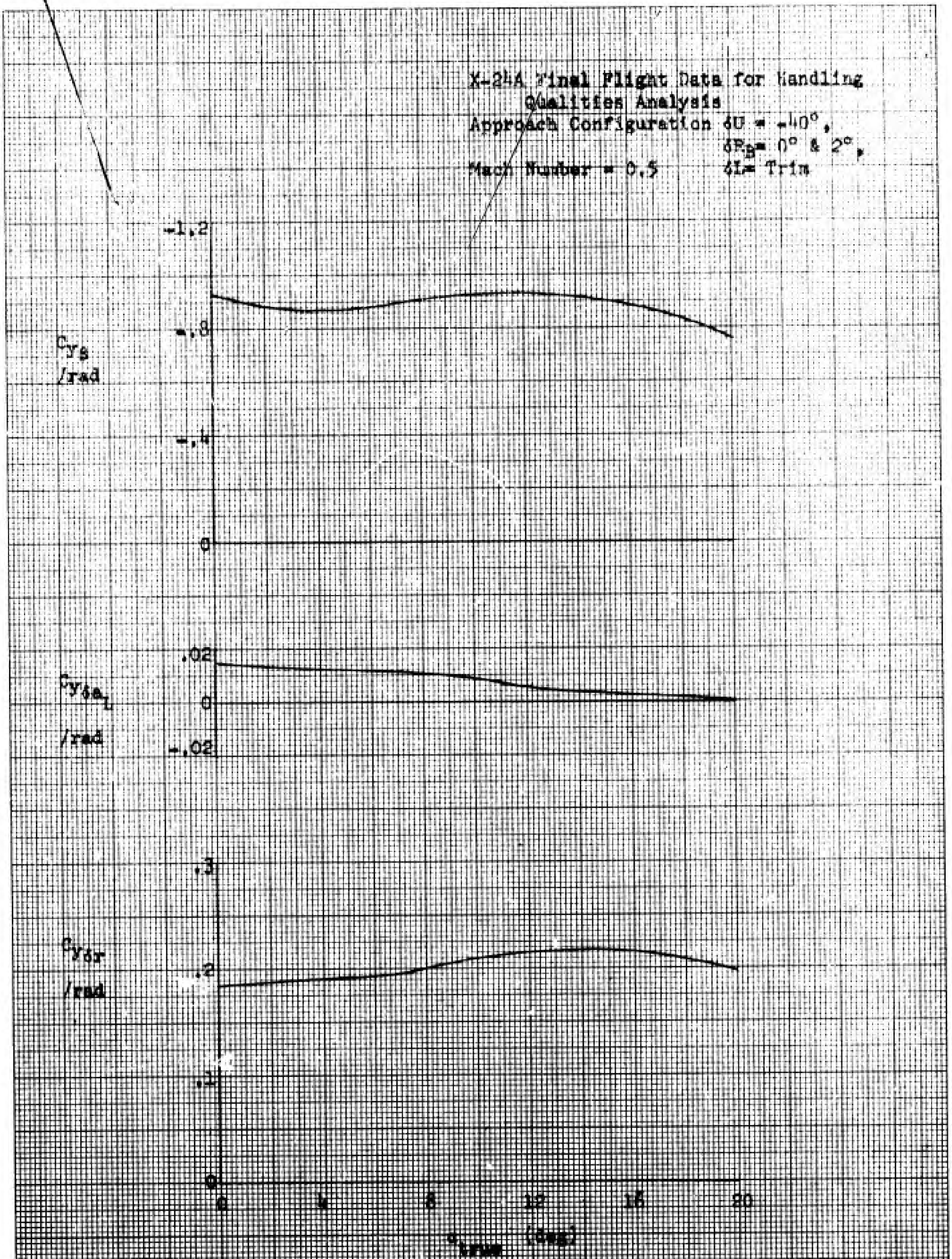


Figure 71. Faired Flight Test Stability Derivatives

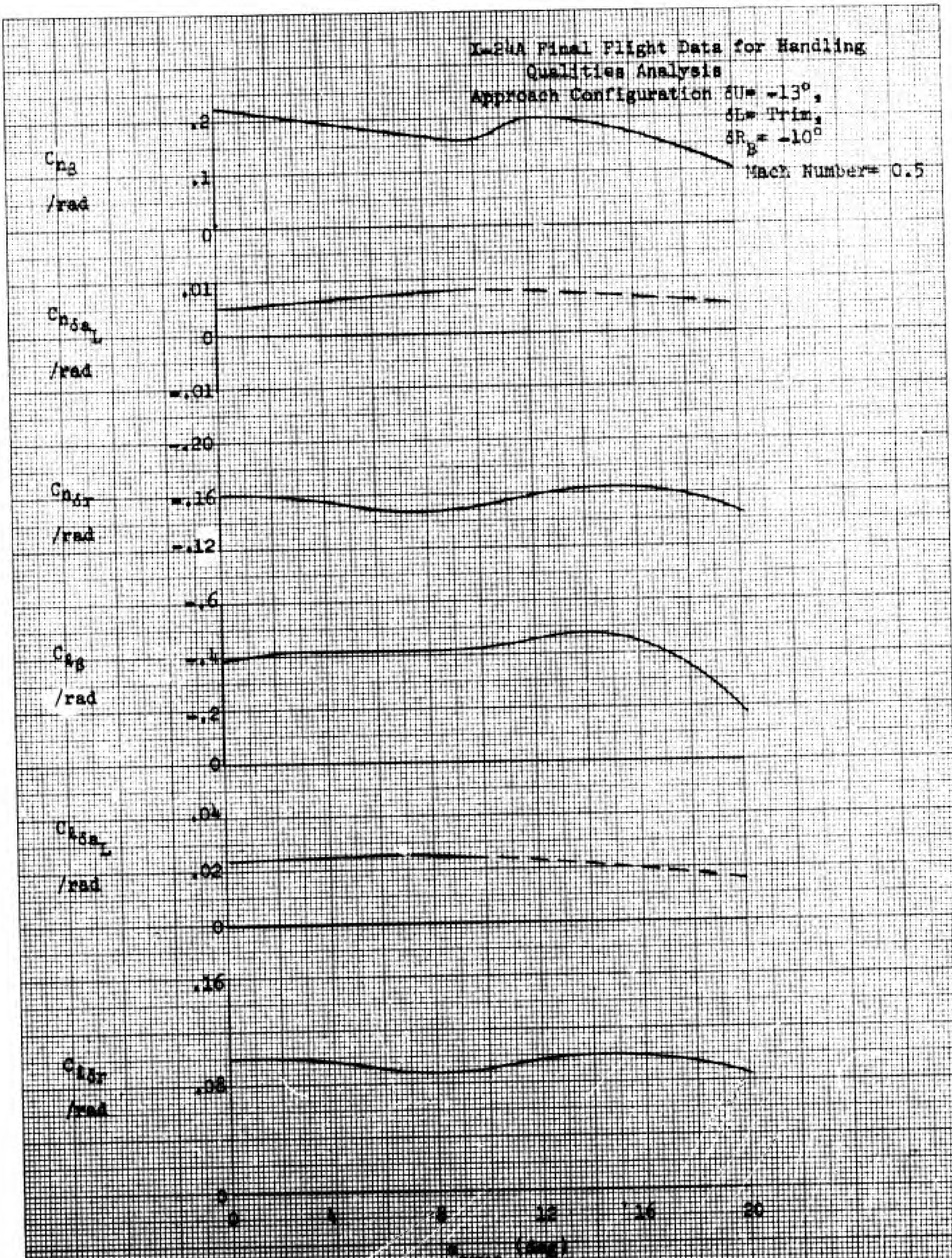


Figure 72. Faired Flight Test Stability Derivatives

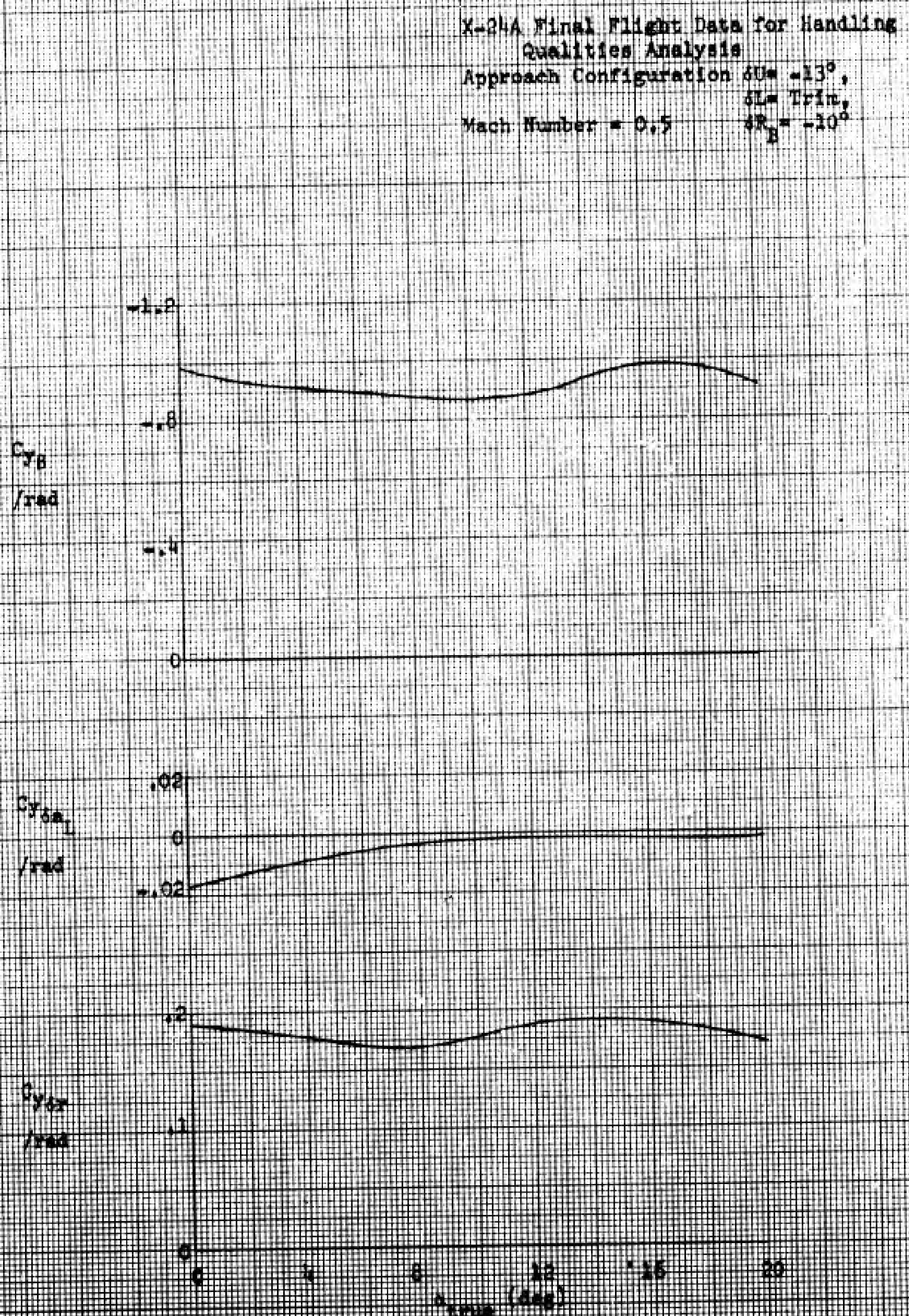


Figure 73. Faired Flight Test Stability Derivatives

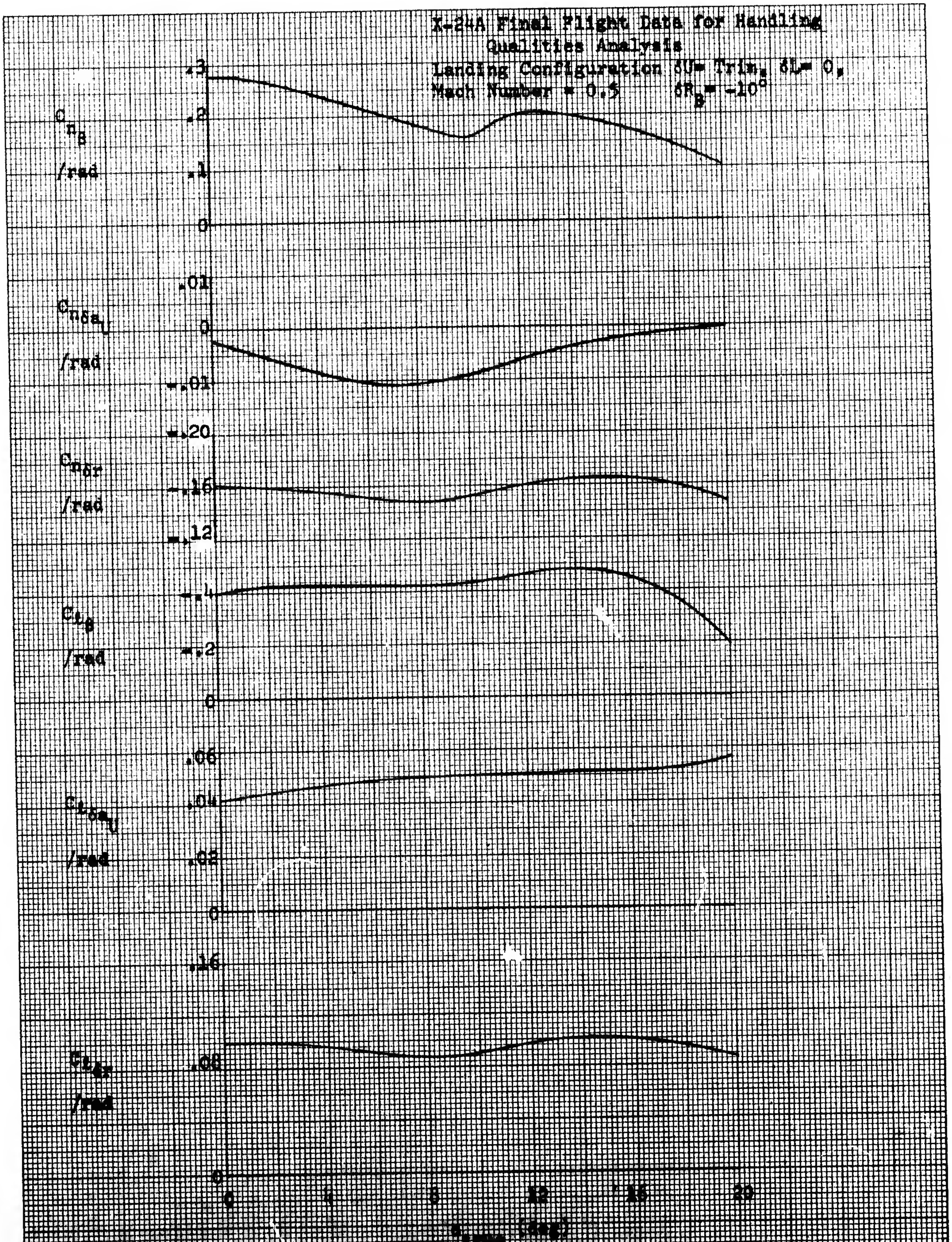


Figure 7[illegible]. Faired Flight Test Stability Derivatives

X-24A Final Flight Data for Handling Qualities Analysis

Landing Configuration δU = Trim, δL = 0, δR_B = $-10°$

Mach Number = 0.5

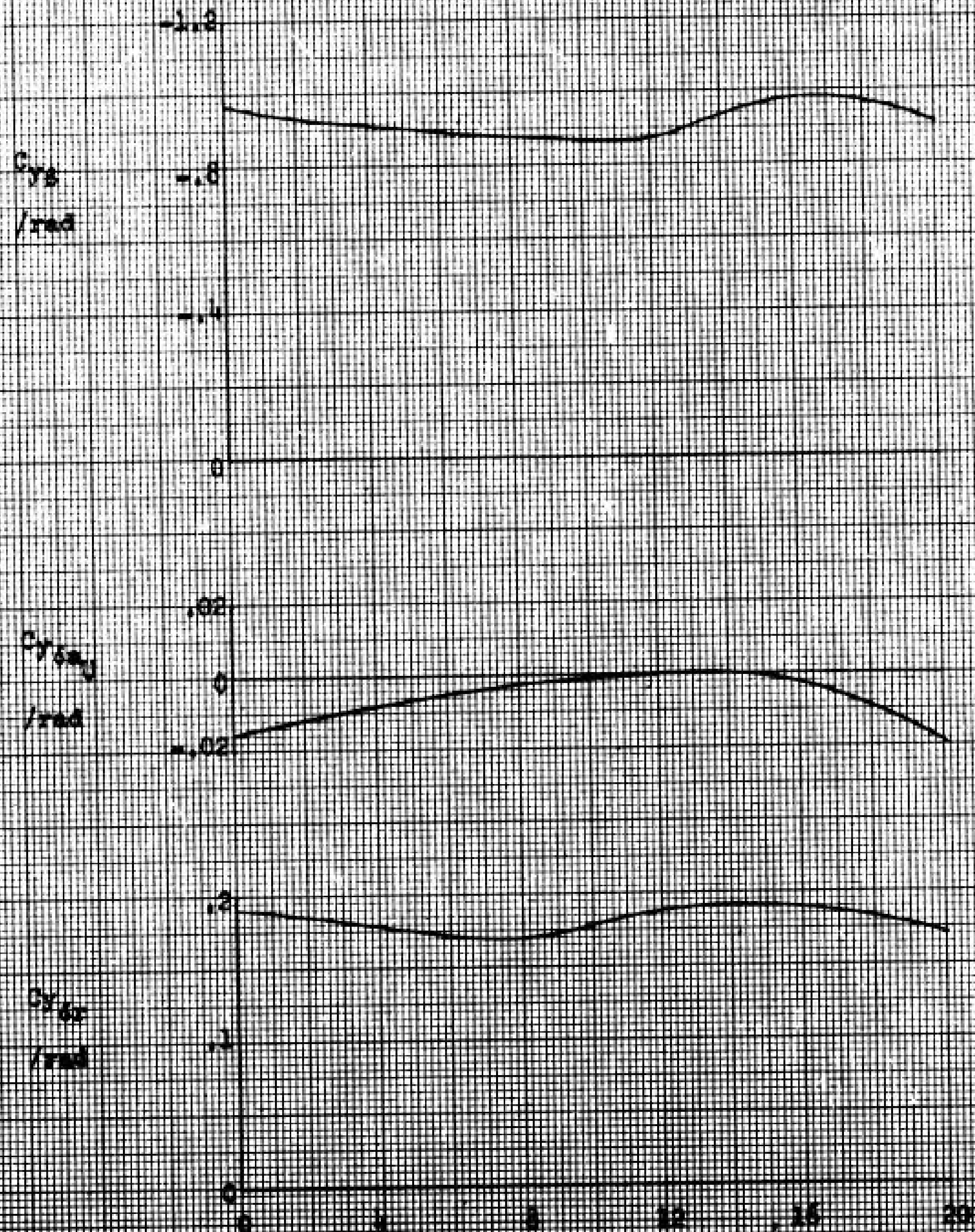


Figure 73. Faired Flight Test Stability Derivatives

APPENDIX III
TYPICAL COMPLETED PILOT QUESTIONNAIRES

PILOT RATINGS

FIRST GLIDE FLIGHT PROFILE

LAUNCH RECOVERY

	Simulator 6 Jan 1969	Actual First Flight 17 Apr 1969
Overall launch recovery task	3 1/2	4
a. Long. attitude control	3	3
b. Bank & Directional control	3 1/2 - 4	4 1/2

FLARE MANEUVER (GEAR UP)

	Simulator	Actual
Overall flare maneuver	3	3
a. Longitudinal control	3	2 1/2
b. Lateral-Directional control	2 1/2 - 3	4

TURN - GEAR UP

	Simulator	Actual
Overall turning maneuver	3	3
I. Rolling into turn		3
a. Bank angle control	3	3 1/2
b. Directional control	3	3
c. Longitudinal control	3 1/2	2 1/2
II. Rolling out of turn		3
a. Bank angle control	3	3 1/2 - 4
b. Directional control	3	3
c. Longitudinal control	3 1/2	2 1/2

HIGH SPEED APPROACH

	Simulator 6 Jan 1969	Actual First Flight 17 Apr 1969
a. Longitudinal control	3	3
b. Lateral-Directional control	3	4 - 5

LANDING MANEUVER

Overall landing task	3 1/2 - 4	3
A. Flare Maneuver	3	3
a. Longitudinal control	3	2 1/2
b. Lateral-Directional control	3	3 1/2 - 4
B. Post Flare Task	4	3 1/2
a. Longitudinal control	3 1/2	3
b. Lateral-Directional control	4 1/2	4 - 5
c. Longitudinal control-gear extension	5	4
d. Longitudinal control touchdown	3 1/2 - 4	3

Roll out

Directional Stability during rollout		2

TECH DEBRIEFING

X-24A Flight X-16-21 Pilot - B

LAUNCH:

1. Did you note any different launch transients?

   I did not notice any difference in launch transients, so question 2 doesn't need an answer.

ENGINE LIGHT & ROTATION:

3. Discuss the trim changes associated with engine light.

   I don't remember any trim changes associated with engine light John, sorry 'bout that! It just didn't seem that I got as high on alpha this time as I have on my previous powered flights.

4. Did the pitch control appear any different than your last flight?

   Yea, it did. It's easier - the pitch task was easier during the boost on this flight than it has been on any other flight. In fact, not just through the boost - I'll have to say on the whole flight, up until low key, I don't recall thinking about it after that. The thing was noticeably easier in pitch - I don't know why - it's just that the airplane did what I was wanting it to do and I wasn't getting a lot of disspersions around the particular point we were shooting for.

5. Rate the task to maintain 17° alpha.

   2.5!

6. Comment on roll power during the rotation.

   Okay, the only time that I was aware of roll power during the rotation was when Jerry asked me to make some heading corrections and the airplane performed adequately there.

CLIMB & ACCELERATION: (Prior to shutdown of #1 chamber)

7. Comment on your attempt to fly a tight boost. Give pilot ratings.

   Okay, I was very pleased with the ability to fly a tight boost prior to shutdown on the first chamber. The airplanes not quite as good as the simulator, I still get an occasional spurious roll input and I am unable to determine where in the heck it comes from, but the airplane starts to roll sometimes without any apparent inputs from the pilot but it's no problem controlling it. Okay, rating the boost profile during this the tight boost - I rate that again at 2.5.

8. Did you note any abrupt lateral trim changes?

   Okay, I don't know if I noticed any abrupt lateral trim changes but I did note some abrupt lateral motions. I didn't associate with a

trim change - I don't think it's a trim change - I think the airplane just goes off a little bit and then I don't think it's a trim change - it doesn't feel like a trim change.

9. Comment on performance differences.

No comment.

10. Did you note any trim change with engine chamber shutdown?

Okay, I did not notice any trim changes during individual chamber shutdowns but I wasn't looking for them. I was concentrating on Mach and then getting right into the task involved. Both cases were roll tasks so I didn't notice trim changes there. (after shutdown #1 chamber)

11. Discuss the roll power at 13° alpha.

The roll power at 13° alpha was adequate. Okay, I didn't notice any tendency toward sluggishness or roll reversal - This 13 alpha was the area in the flight were I mentioned over the air about the roll non-linearity. I don't recall this being the case at the lower alpha. Okay, the non-linearity we're speaking about means that the airplane is rather sensitive with the initial small inputs to the aileron and as the input gets larger why the roll response decreases.

12. Give pilot ratings for this period.

Okay, for the pilot rating during this period - this probably was the most difficult part of the boost and the pilot rating there would be 3. (after shutdown #3 chamber).

13. Did you note any trim change with #3 shutdown?

Don't recall any trim change when I shut down number 3.

14. Discuss the roll power at 10° alpha.

Roll power at 10° alpha again was adequate although I didn't have as much time here. I stayed a little too long at 13 alpha with 3 chambers running so I didn't have a heck of a lot of time at 10 alpha but I didn't have any roll problems.

15. Discuss your clues for final shutdown.

No answer for question 15.

16. Any significant trim changes with final shutdown?

Okay, significant trim changes for final shutdown - I made a note to watch the transients this time, I had Jerry remind me to watch the transients so it essentially was a hands off maneuver and I did notice about a 2 to a 3° trim change in pitch and a slight roll off at shutdown. I don't know which way it rolled - it didn't roll a heck of a lot, I don't think it rolled more than 10° but it did roll a little bit and I got a little pitch down - much less than the simulator.

17. Did you use any rudder during boost?

I didn't intentionally use any rudder during the boost.

DATA MANEUVERS:

18. Discuss the roll response observed at 5° alpha. Give pilot ratings.

Okay, the roll response at 5 alpha was just about what I'd like to see it in the airplane. I wouldn't like to have it any more sensitive than it is and there wasn't any tendency towards sluggishness or roll reversal - it looks like just about the right combination right there for this angle of attack. Okay, rate this 3.

19. Comment on A/C response to dampers off rudder & aileron doublets at 11° alpha.

The airplane responded almost exactly like I'd seen in the simulator from the rudder pulse - in fact I probably booted a little bit harder than I had intended to so maybe we're getting more response from the rudder than what the simulator showed because I told myself to give it just a little bit of a boost and I didn't hit it very hard and it went out pretty good so we might have just a little bit more response in the airplane to rudder. The aileron - the hard thing to judge in aileron response in the simulator and compare it to an airplane because you don't have the motion cues there and you expect to see a big bank angle change and you don't. You know you put something in and you say good grief nothing happened and another problem was, while I was letting this thing damp out - the theta oscillations of the airplane rolled one way so I couldn't give it a good doublet so we did triplet. As we said, the first one was to try to get the airplane started back the other way and then I snuck a little in but this was the one area the airplane seemed to be a little sluggish, but here again it's hard to give a qualitative rating on an aileron pulse because you don't fly an airplane with aileron pulse - this is just for you data folks.

20. Any comments on pushover-pullup?

It was a real smooth maneuver. The most comfortable pushover-pullup or the most comfortable data maneuver I've done on the airplane - it was just so straightforward and pretty, just like it shows on the records. It went down - I pushed it down. I thought I saw between 0 and 1° on alpha and pulled it back up to 20 and I did tell you about the lateral change that I got during the pushover - I could feel the airplane roll and put the aileron in and that stopped it and then back up to 20 alpha and back down - it was extremely smooth and comfortable maneuver. No overshoots in pitch - the pitch damping was fantastic.

21. Were you aware of any trim changes with jettison?

I was not aware of any trim changes with jettison and darn it I meant to look at that.

22. Discuss the configuration change. (a) Longitudinal (b) Lateral- did you note any tendency to PIO?

Okay, on the configuration change - it looked to me like a heck of a lot like the simulator as far as the alpha change goes, I started at 15 and I pushed the button and sure enough the alpha dropped off - and it's a little task to control it longitudinally, you just can't hold the constant alpha on it - it is more of a task and it is a little more difficult - it's nothing disturbing at all but if you want to hold a solid alpha - it's just pretty hard to do - and I think if you want to see what it's like, go fly the simulator because it's exactly like that! It was just amazing, I was bound and determined I was going to hold the alpha at 15 and in the simulator I can't do it - I always drop off and I did the same old PIO thing again but it seemed to me to be lower amplitude and a little bet higher frequency this time and I don't think it lasted as long.

PATTERN & LANDING:

23. Discuss energy management during pattern.

Okay, energy management during the pattern wasn't any particular problem - I started out high and I ended up high on energy. I did use the speed brakes during the early part of the flight but I wanted to get the airplane all cleaned up and leave it so that I could evaluate this KRA. So I did start out high at the 90° position and I did indeed end up a little high on energy all the way through but I don't think it's fair to rate this flight from energy management standpoint or from a touchdown standpoint because that wasn't the objective. I was doing a research maneuver all the way down to touchdown so I think we ought to keep that in mind.

24. Discuss the handling qualities & riding qualities. What KRA schedule was used? Give pilot ratings.

Okay, the handling qualities and riding qualities, I get the impression that upping the KRA was the same as giving the guy more turbulence - you get the same sort of feel, whether it's a riding qualities or whether it's intuition or what it is but something there just tells you that the airplane is a little more sensitive and it just looks to me like with a 50% KRA I can get the same sort of feeling by flying a heavy light turbulence or a moderate light turbulence or whatever we call it - okay, I think the best KRA schedule that we've had for overall riding and handling qualities in the pattern would be the KRA schedule we had for flight number 13. So as John said, it's the point 7 Mach repeater setting.

OTHER:

25. Did you make any aileron or rudder trim changes during flight?

I did not make any aileron or rudder trim changes during flight.

26. Discuss the increased roll breakout forces & pitch/roll harmony.

I get the impression that the increased roll breakout forces have helped. I think that the real answer is going to be from Jerry when he flies since he had the most problem with the PIO during the boost - I could tell a change, a difference in the configuration

change and it seemed to be for the better. I prefer the forces we have now. The harmony looks good. When you sit in the airplane and feel that the harmony doesn't look good you say boy there's a lot less force in pitch then there is in roll and yaw but once you get in and fly it, why I didn't see anything that was unharmonious or whatever they say. I like the way it is.

27. Were all cockpit displays, switches, pressure suit etc. satisfactory? Okay, all cockpit displays, switches, pressure suit were satisfactory. The only comment I guess - when I went to maximum vent, why I cut off the air to the cabin and it didn't pressurize.

28. Do you have any recommendations for changes prior to next flight?

Okay, we've considered putting something over the top of the cockpit to keep out some of the sunrays over the area that we don't normally look out during the flight. I think this is a good idea. That would be my only recommendation - this thing over the cockpit and I suggest we keep using this tarp that we threw over the canopy.

APPENDIX IV
LONGITUDINAL TRIM CURVES

Figures 76 thru 93 are on the following pages 126 thru 143

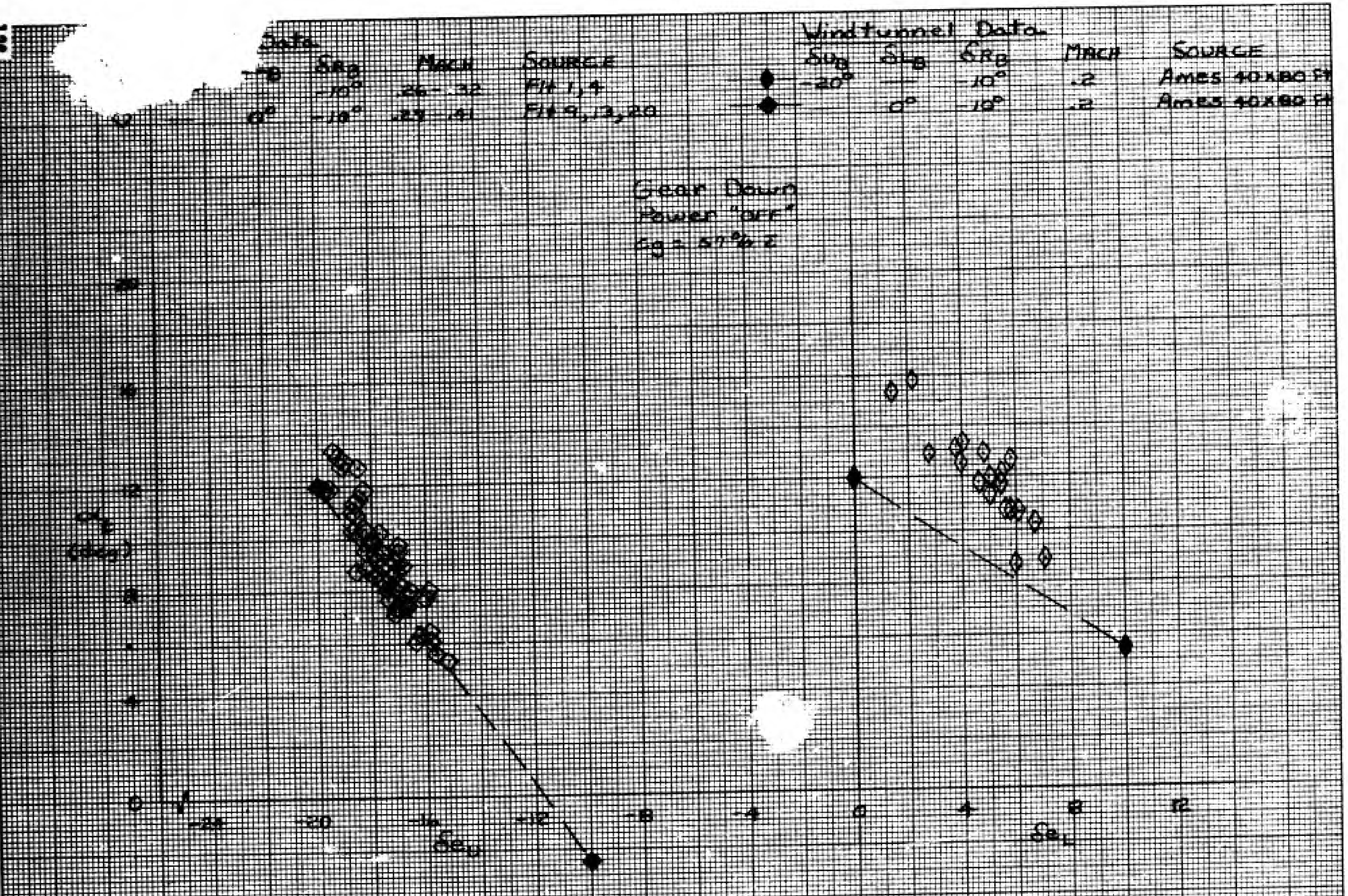


Figure 76. Longitudinal Trim Curves

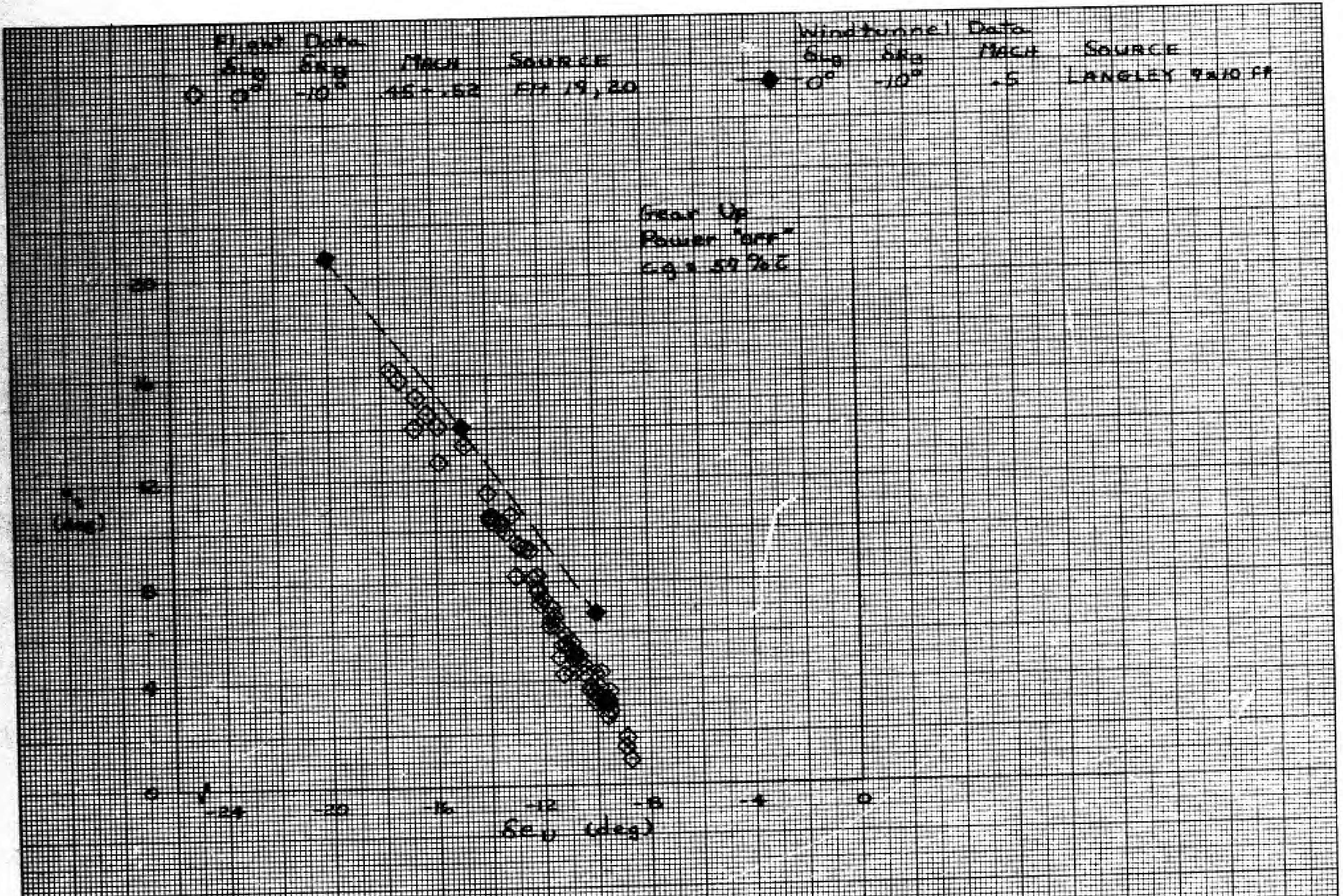


Figure 77. Longitudinal Trim Curves

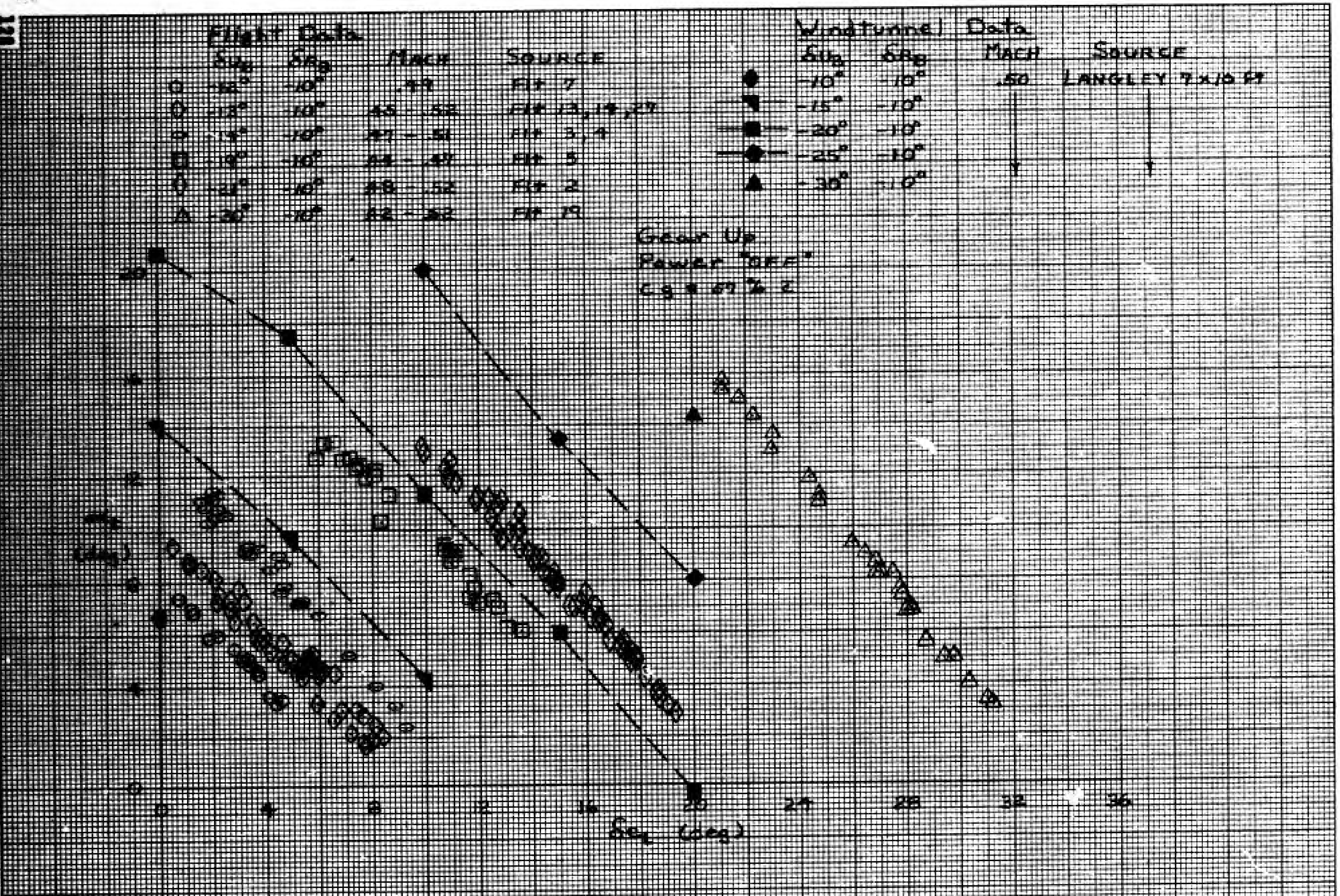


Figure 78. Longitudinal Trim Curves

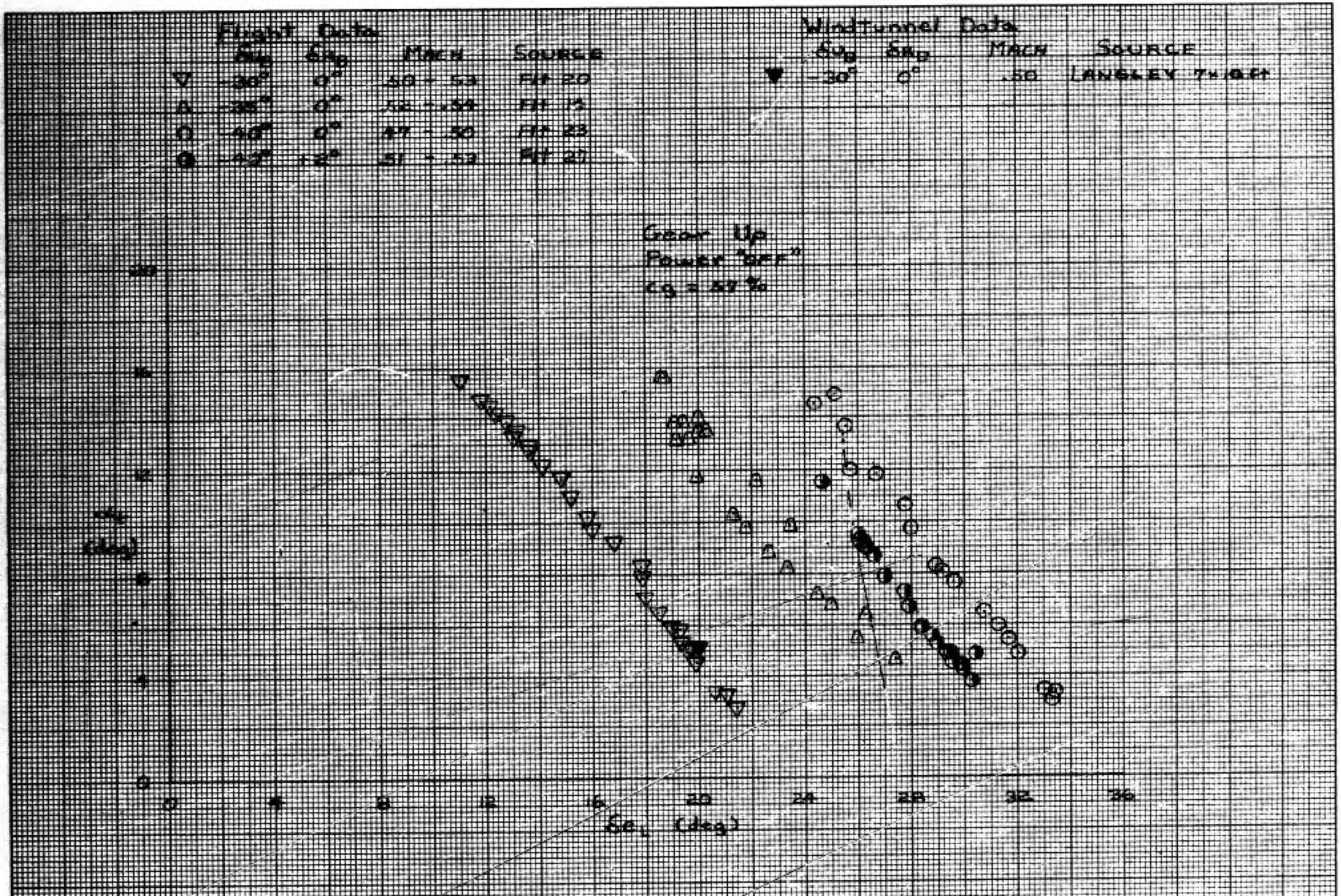


Figure 79. Longitudinal Trim Curves

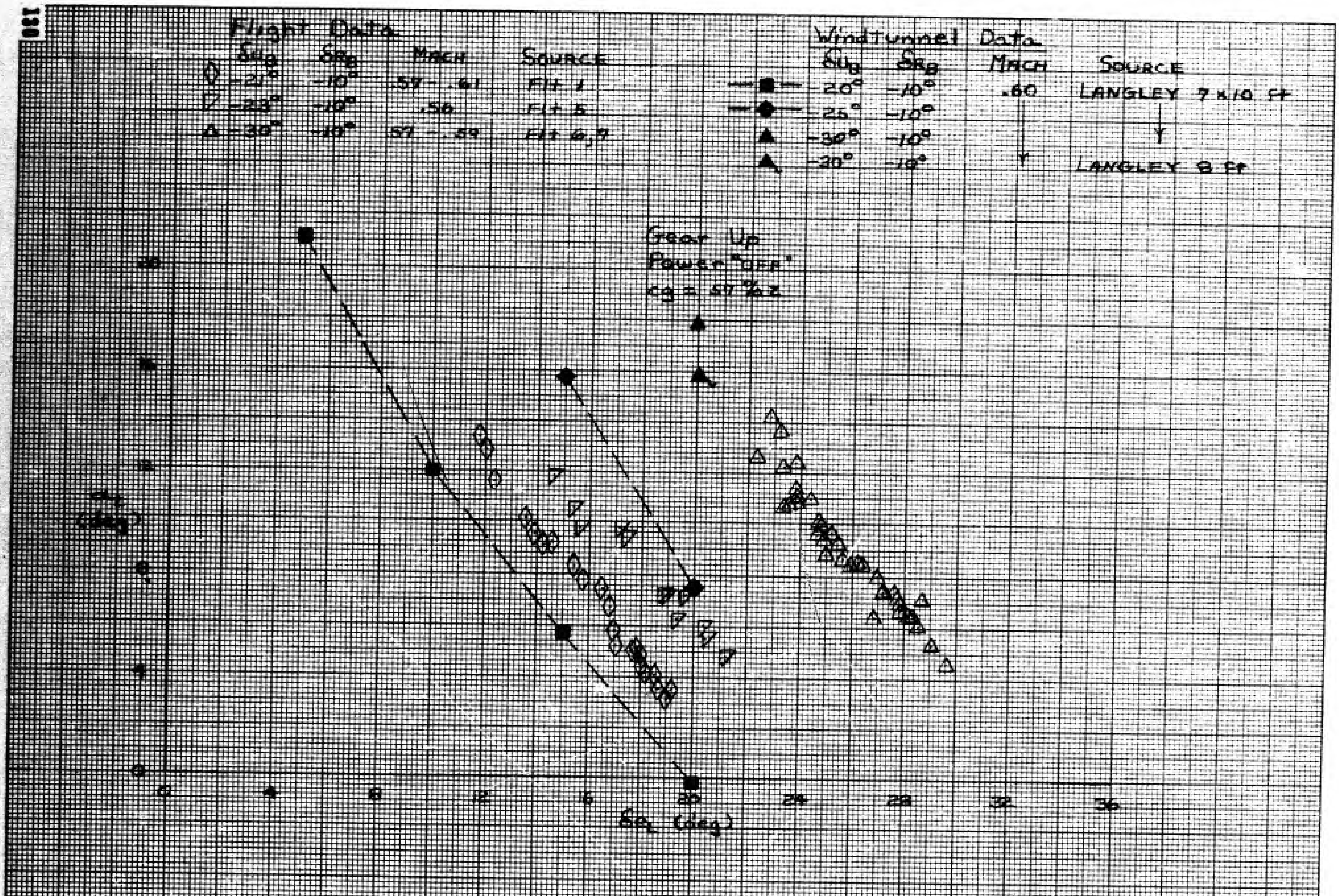


Figure 80. Longitudinal Trim Curves

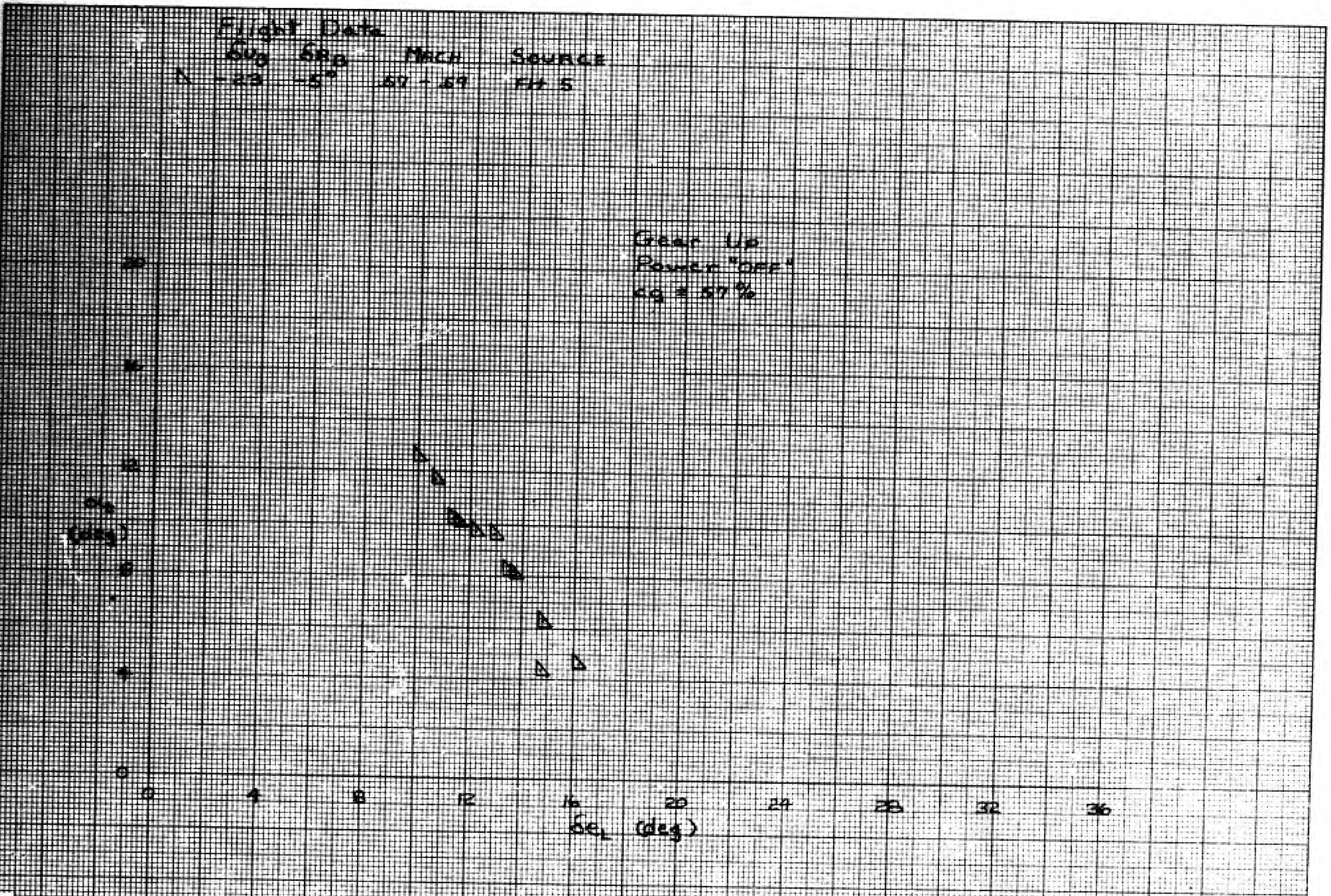


Figure 81. Longitudinal Trim Curves

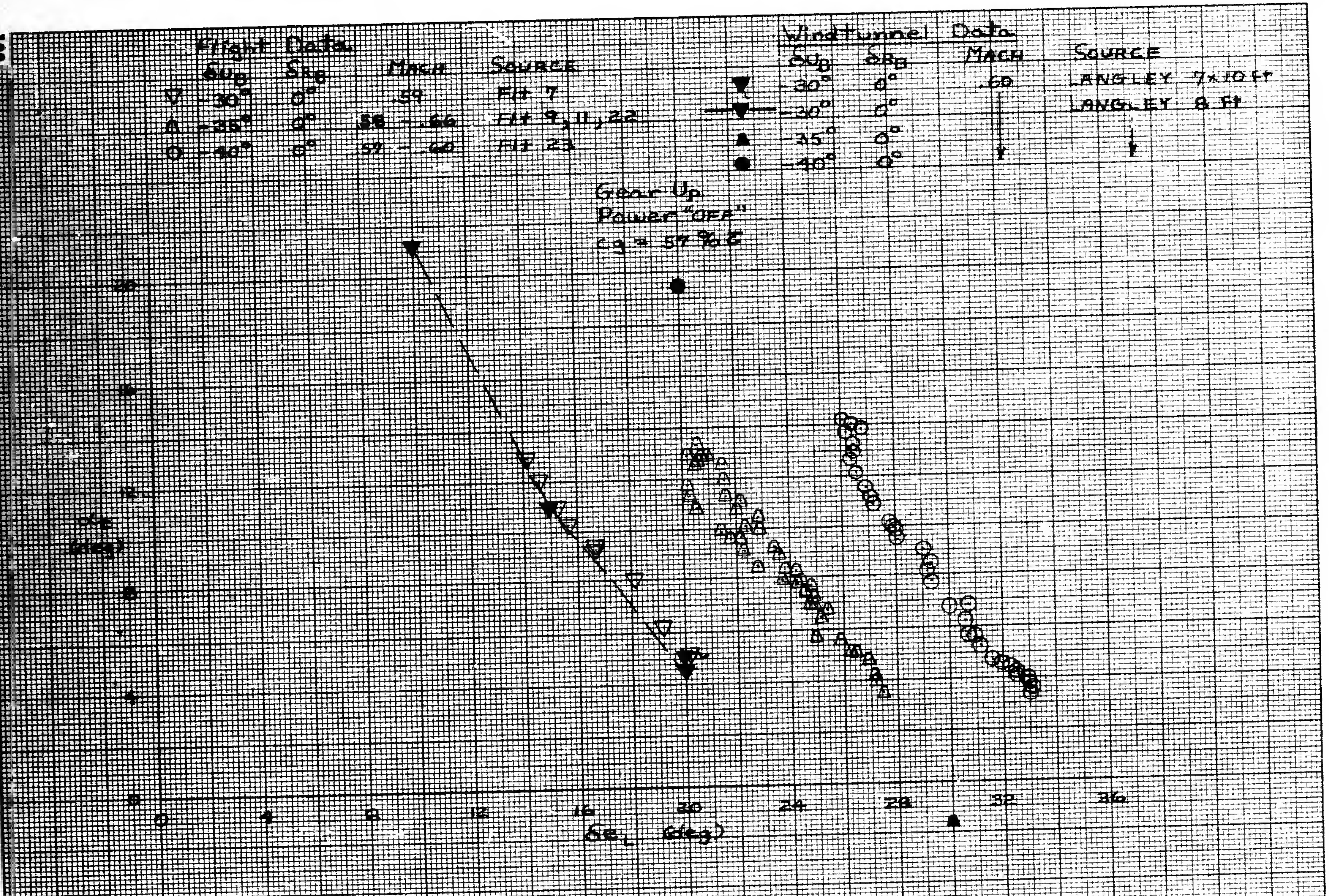


Figure 82. Longitudinal Trim Curves

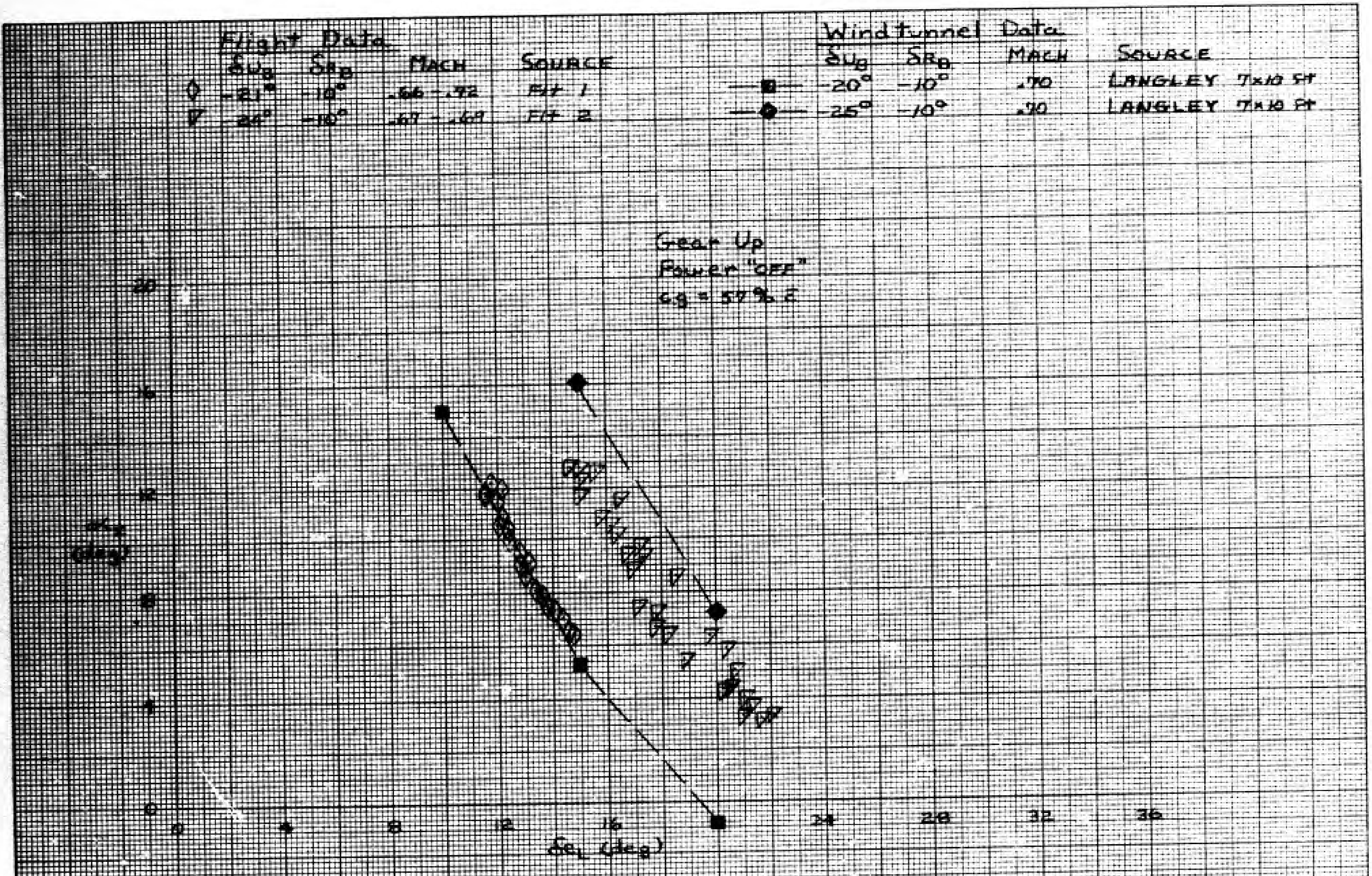


Figure 83. Longitudinal Trim Curves

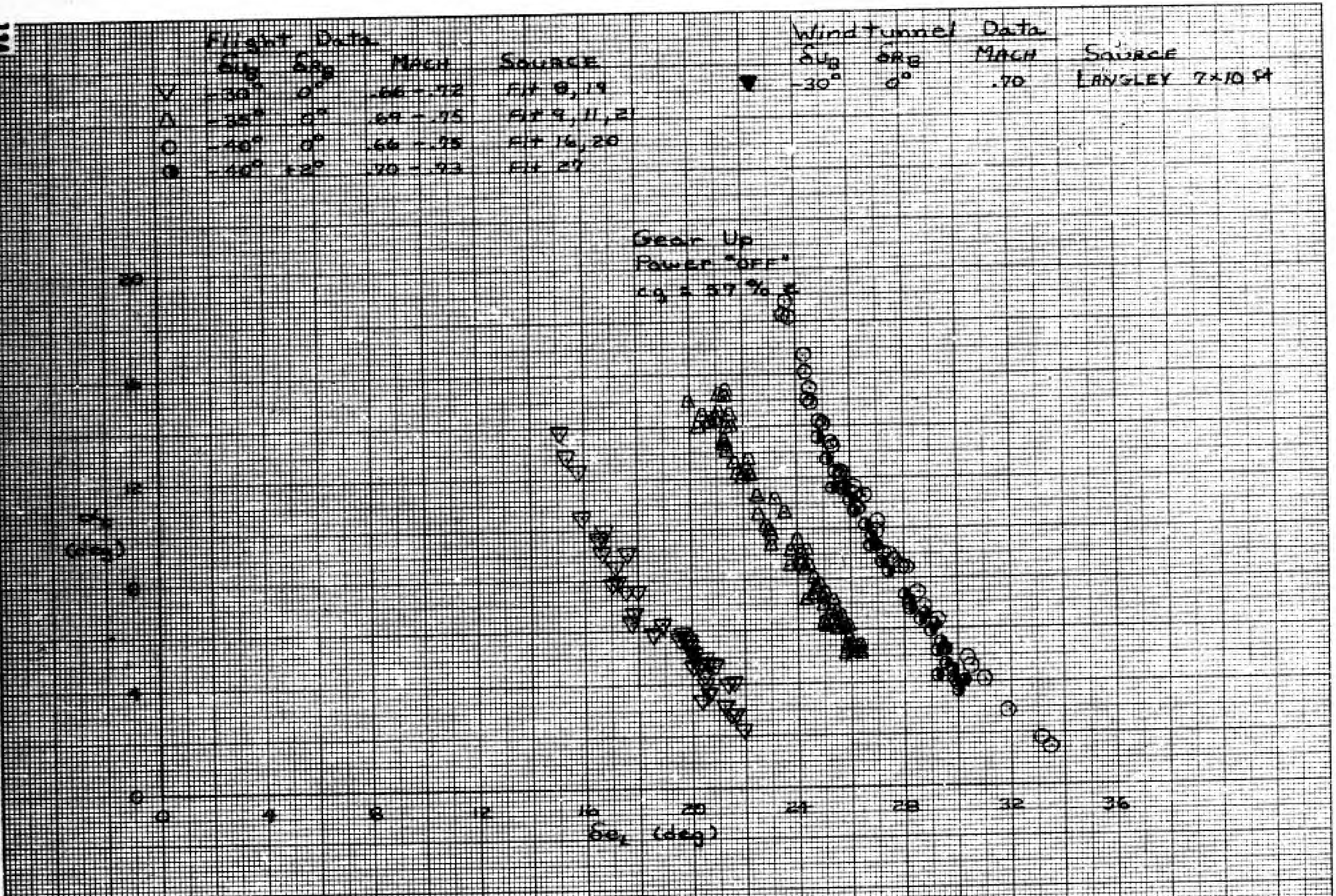


Figure 84. Longitudinal Trim Curves

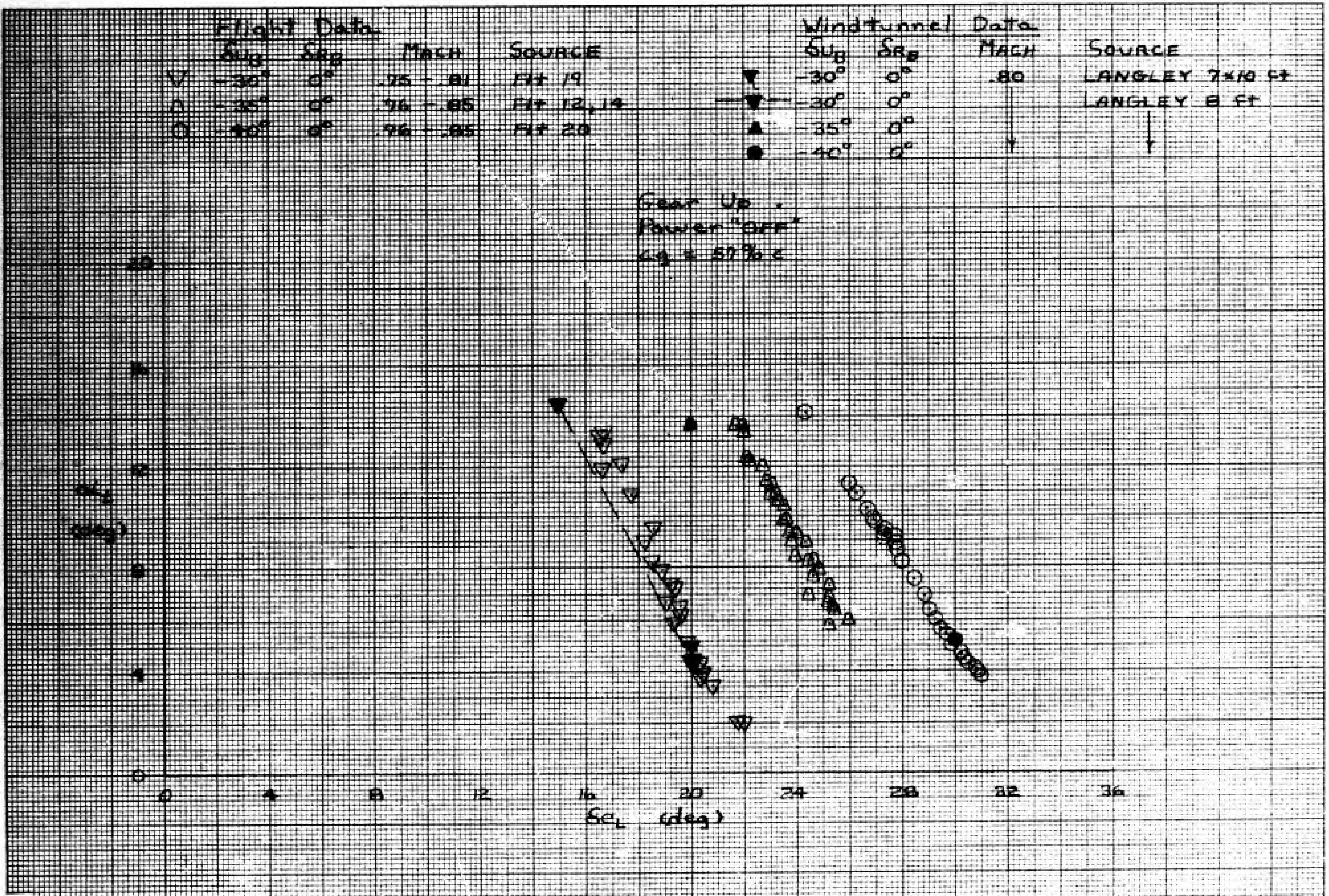


Figure 85. Longitudinal Trim Curves

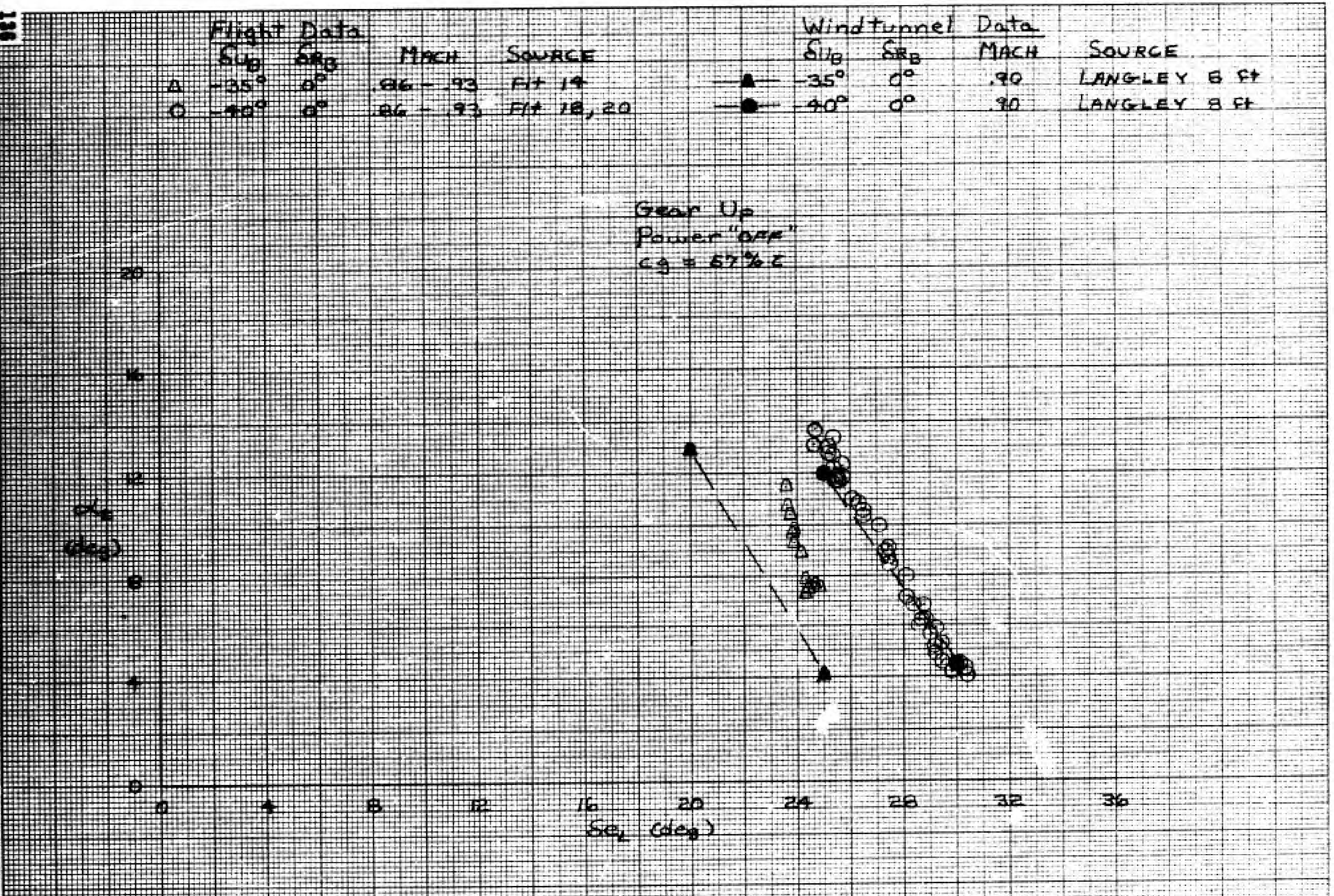


Figure 86. Longitudinal Trim Curves

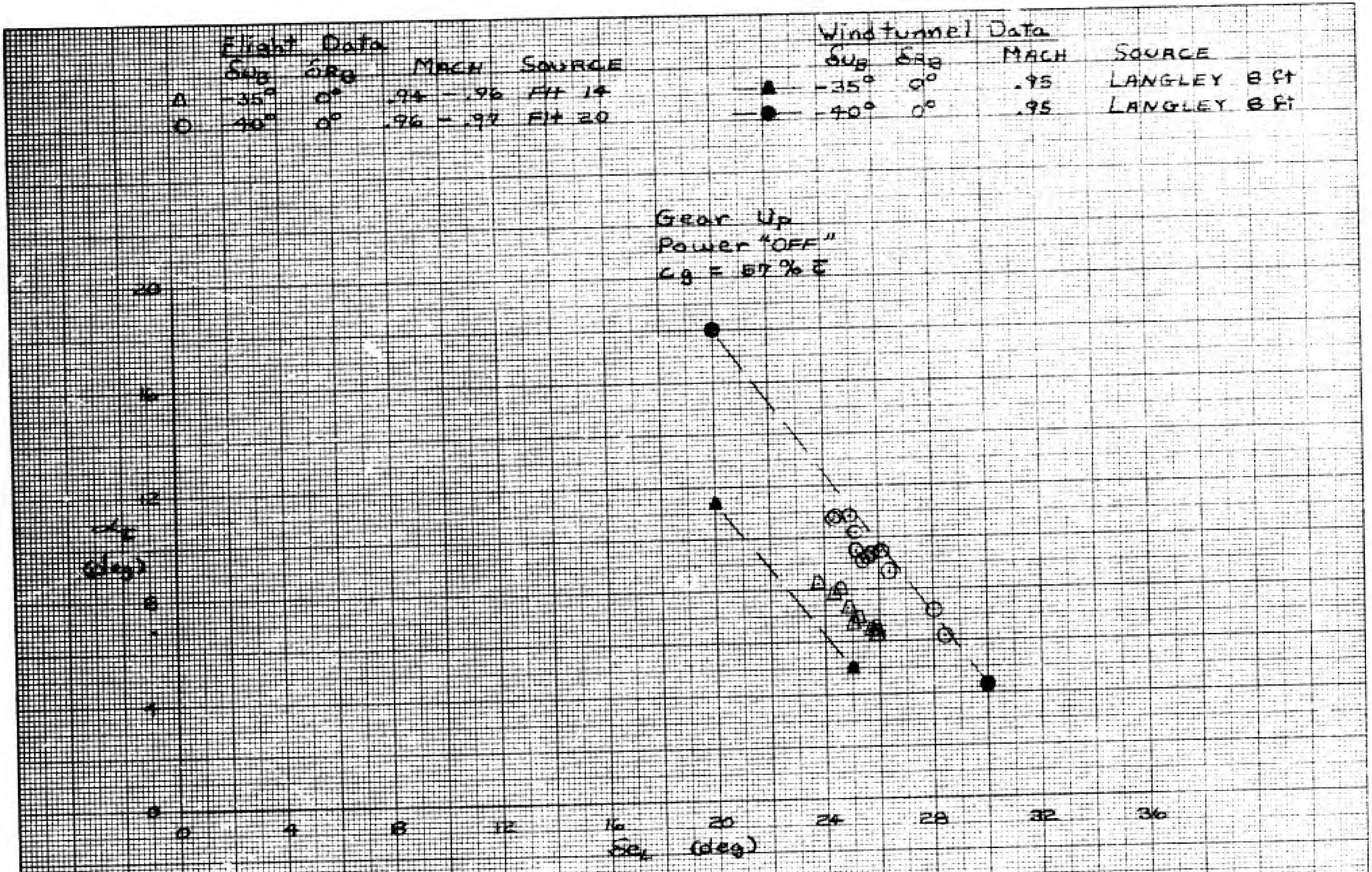


Figure 87. Longitudinal Trim Curves

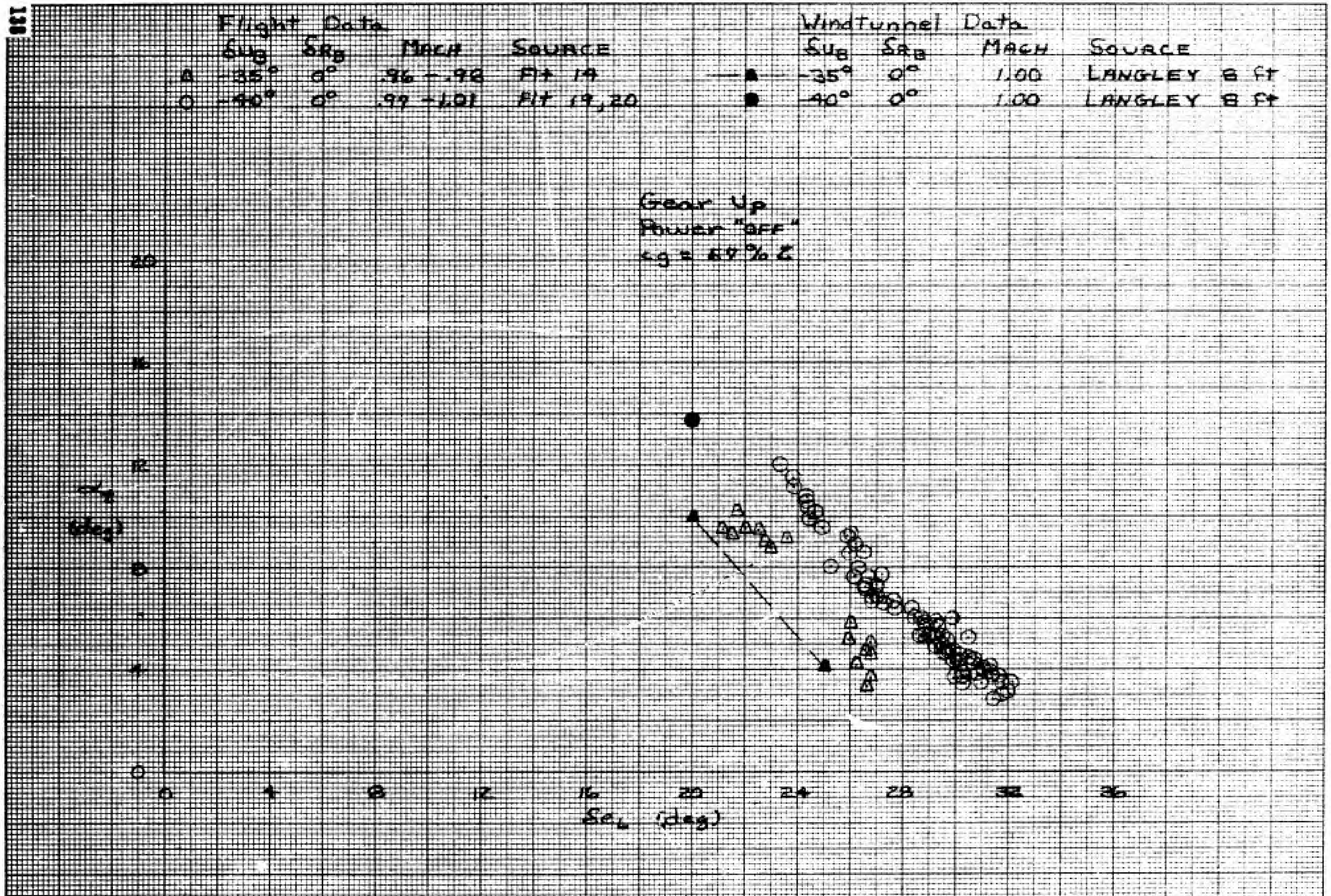


Figure 88. Longitudinal Trim Curves

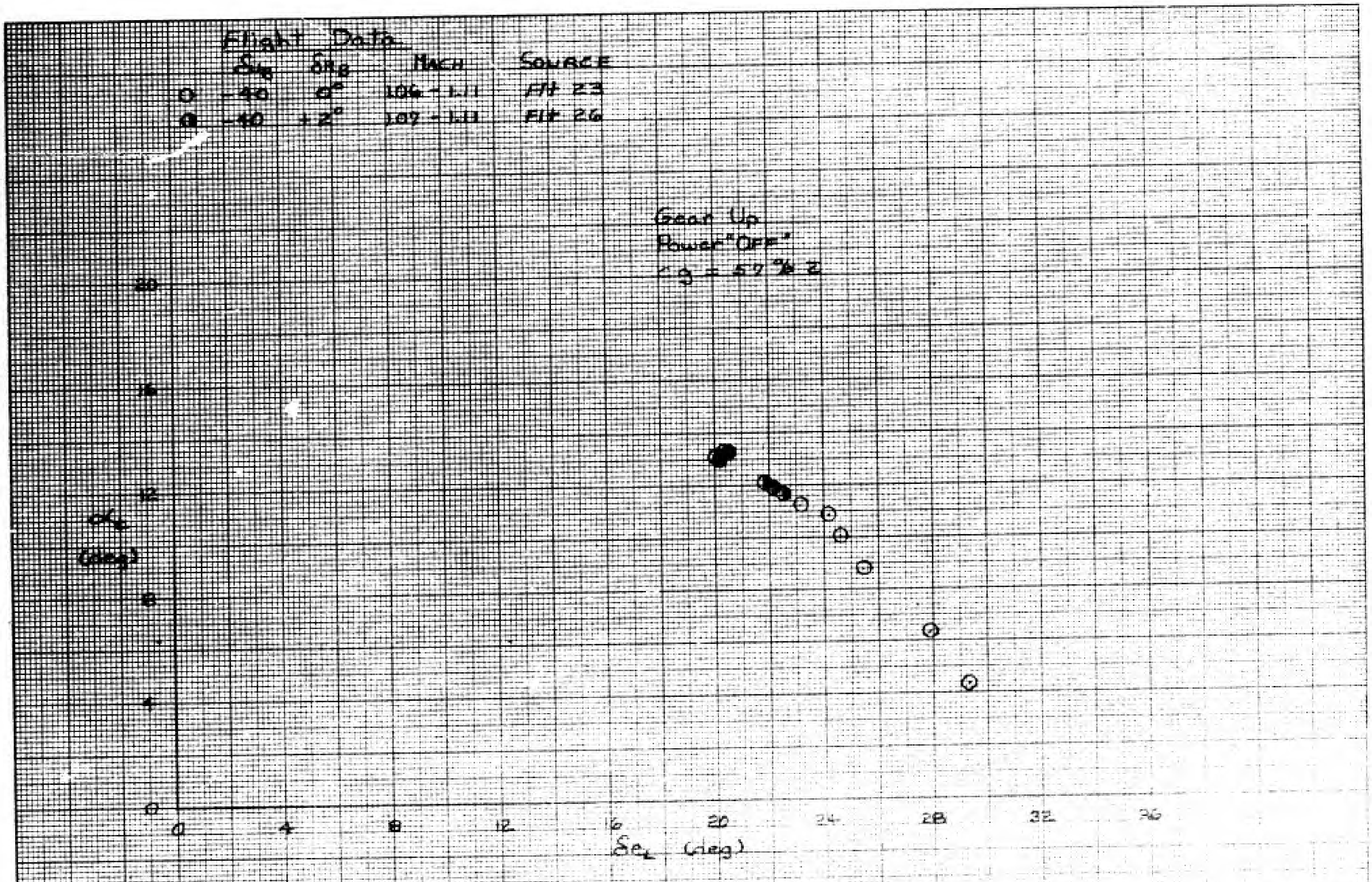


Figure 89. Longitudinal Trim Curves

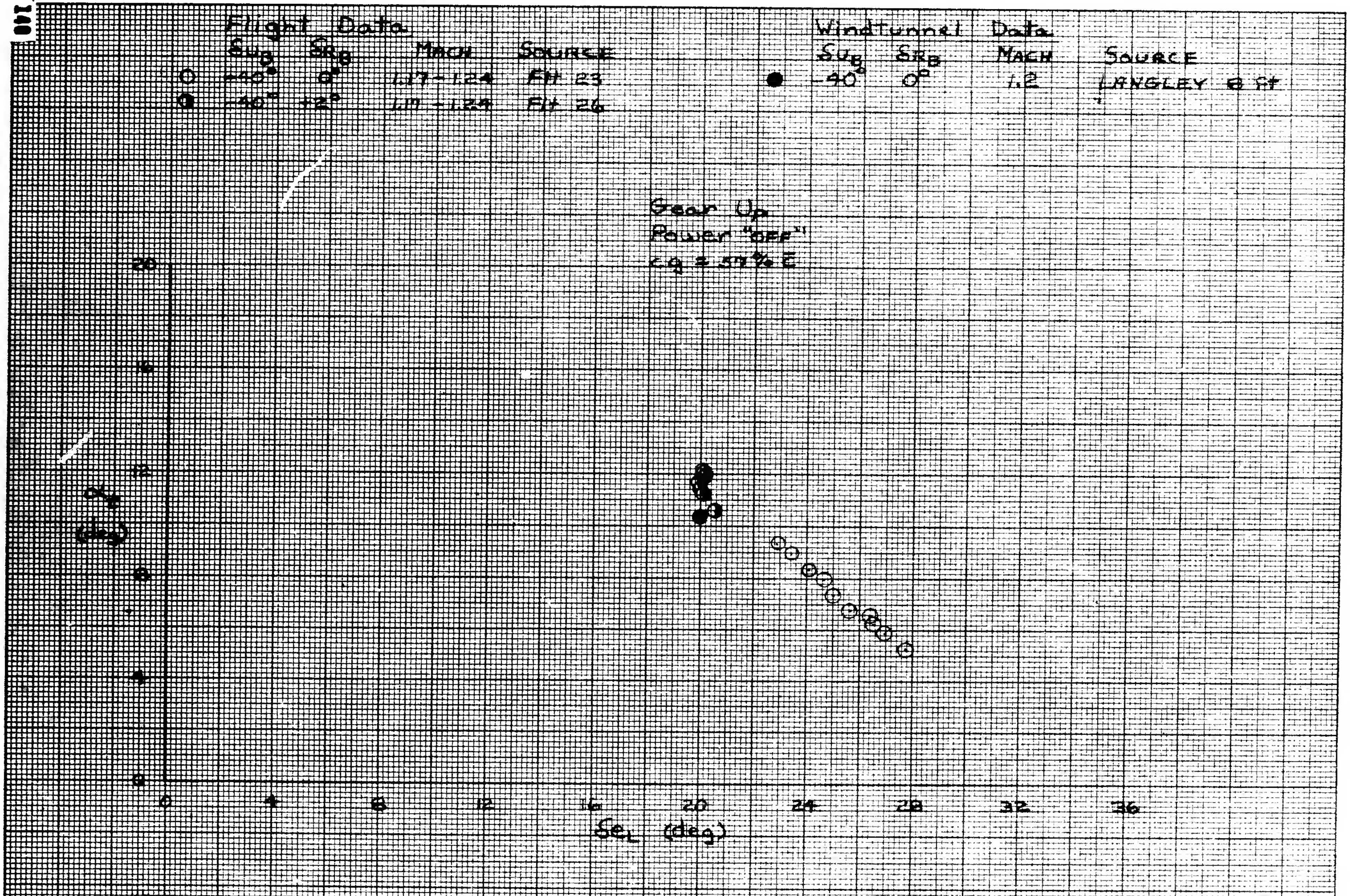


Figure 90. Longitudinal Trim Curves

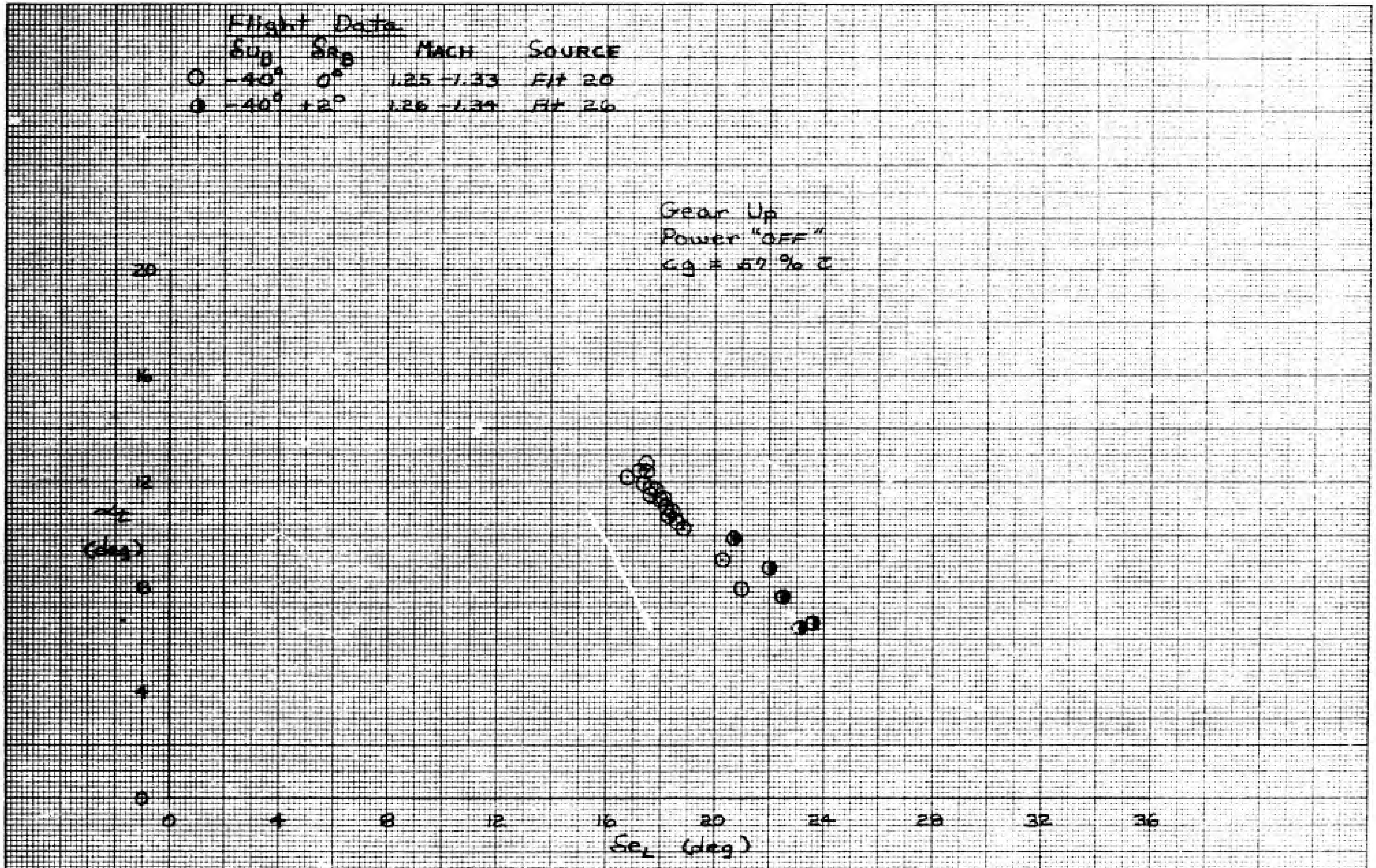


Figure 91. Longitudinal Trim Curves

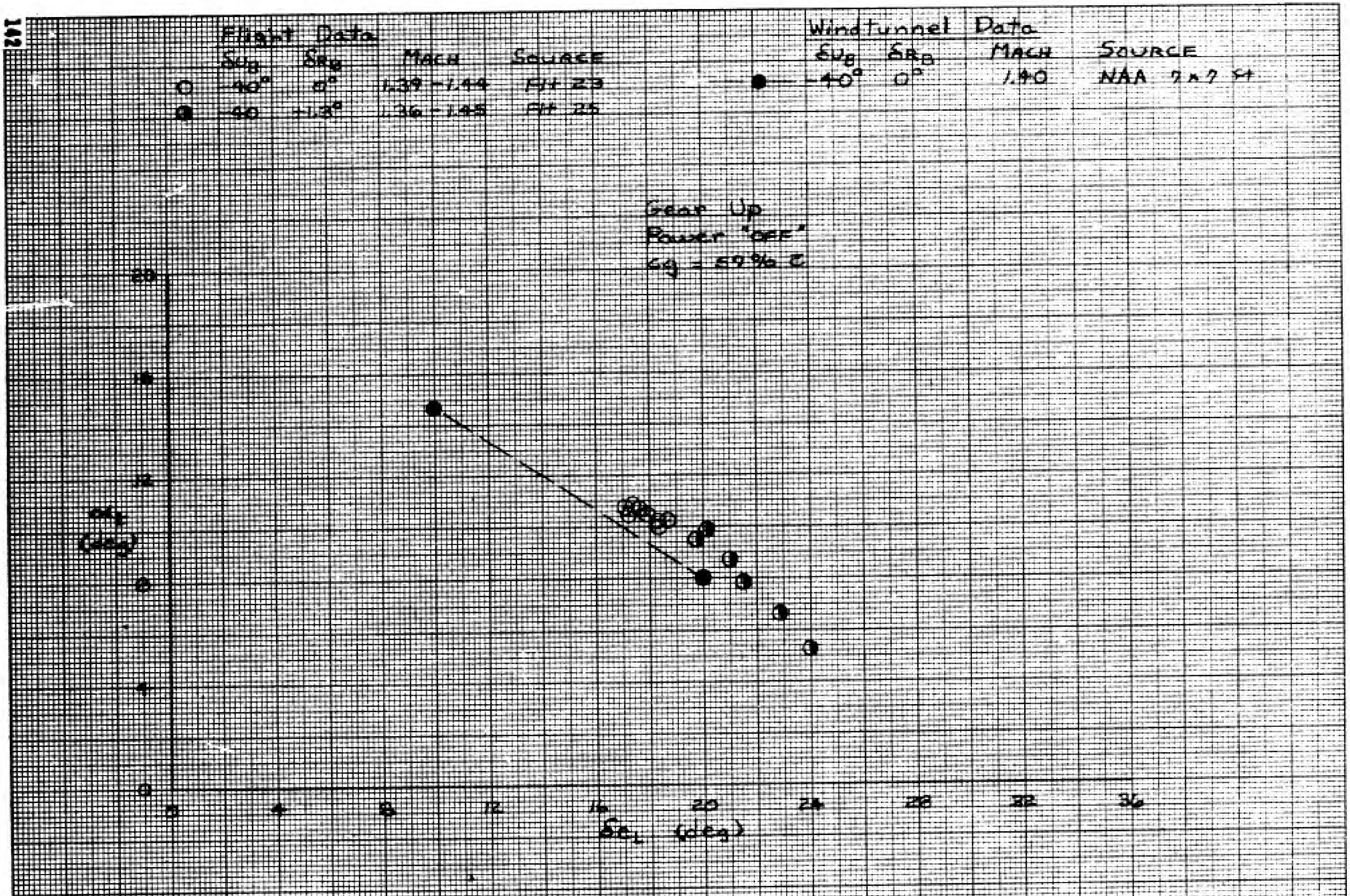


Figure 92. Longitudinal Trim Curves

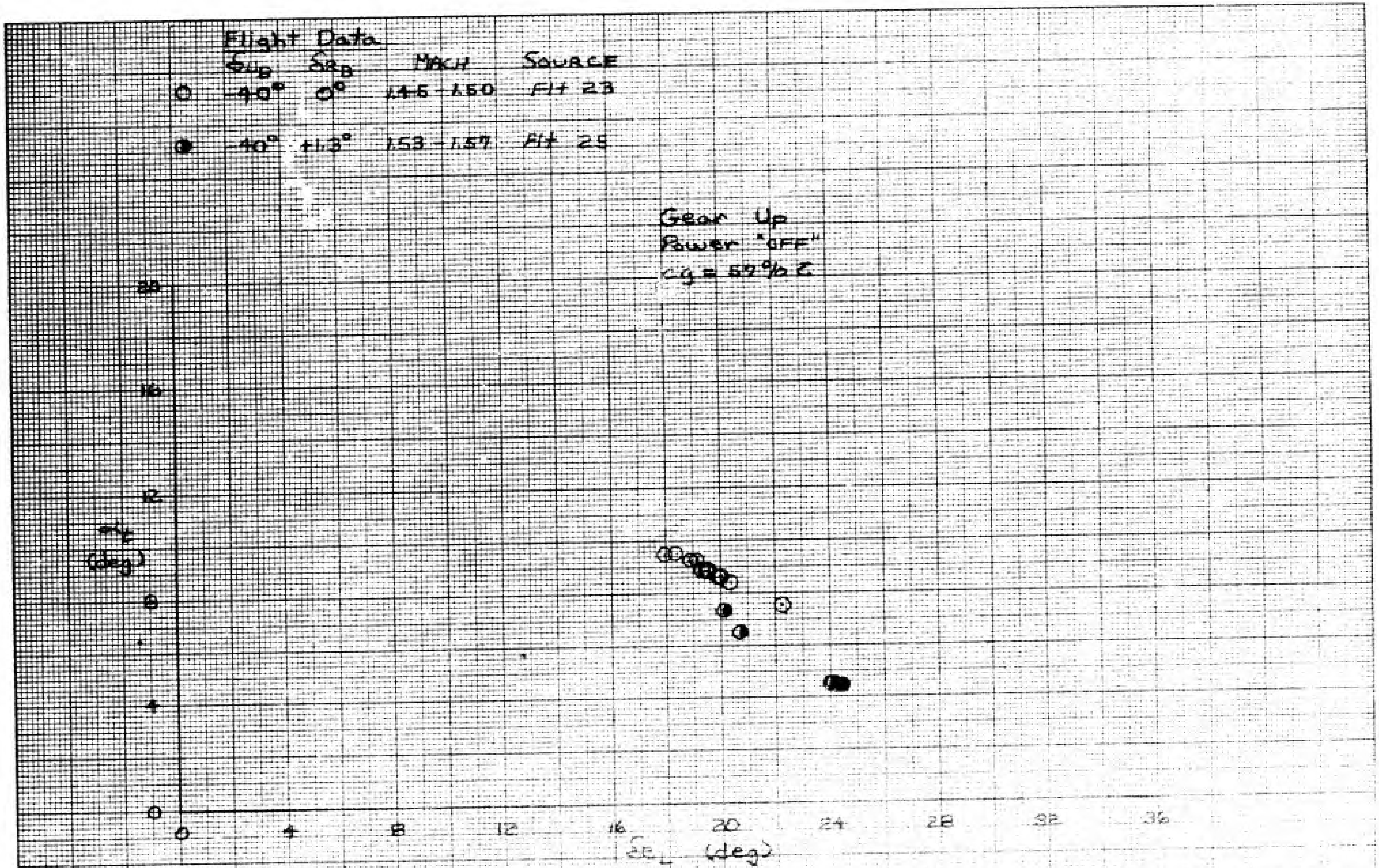


Figure 93. Longitudinal Trim Curves

APPENDIX V
DISCUSSION OF ROOT LOCUS ANALYSIS TECHNIQUES

A root locus plot can be a very useful tool for analyzing the response of dynamic systems. To better understand this tool, some fundamentals of the analysis method are presented here.

Any dynamic system can be represented by a set of differential equations which describe the motion at some future time. As a simple case, consider a spring-mass-damper system. The differential equation for this system is

$$m \frac{d^2x}{dt^2} + f \frac{dx}{dt} + kx = r(t)$$

where

x = displacement from reference

m = mass

f = friction

k = spring constant

$r(t)$ = system input

Using Laplace transforms this equation can be rewritten as

$$X(s) = \frac{(ms + f)\ x_o}{ms^2 + fs + k}$$

The denominator of this polynomial is called the characteristic equation for this system, and the roots determine the nature of the time response to a given input. These roots may be real or complex. In the case of complex roots, the real portion of the root is equal to $\zeta\omega_n$ where

ζ = damping ratio

ω_n = undamped natural frequency

The imaginary part of the root is equal to $j\omega_d$, the damped frequency.

For a real root, the system response is non-oscillatory (that is, $j\omega_d = 0$), and the root is equal to $1/\tau$ where τ is a time constant of the system.

This type of analysis works very well for a single-degree-of-freedom system with only one differential equation. For a more complex system, such as an aircraft, a method known as state variables is used. For the aircraft, the matrix x is defined:

$$x = \begin{bmatrix} P \\ R \\ \beta \\ \phi \end{bmatrix}$$

With some linearization, differential equations can be written for these.

$$\dot{P} = L_p \cdot P + L_R \cdot R + L_\beta \cdot \beta$$

$$\dot{R} = N_p \cdot P + N_R \cdot R + N_\beta \cdot \beta$$

$$\dot{\beta} = P \sin \alpha - R \cos \alpha - Y_\beta \cdot \beta + \frac{g}{V} \phi$$

$$\dot{\phi} = P$$

From these equations a matrix can be determined which describes the $\dot{x}$ matrix ($\dot{P}$, $\dot{R}$, $\dot{\beta}$, $\dot{\phi}$) in terms of the x matrix.

$$\dot{x} = A \cdot x$$

$$\begin{bmatrix} \dot{P} \\ \dot{R} \\ \dot{\beta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} L_p & L_R & L_\beta & 0 \\ N_p & N_R & N_\beta & 0 \\ \sin \alpha & -\cos \alpha & Y_\beta & \frac{g}{V} \\ 1 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} P \\ R \\ \beta \\ \phi \end{bmatrix}$$

The A matrix (which can be modified to include control surface actuator transfer functions, washout filters, I_{xz} terms, etc.) effectively describes the equations of motion for the aircraft, and is analogous to the characteristic equation described before. Once this matrix is determined, eigenvalues of the matrix are found (through matrix algebra done by a digital computer), and these eigenvalues are the roots of the system.

The limitations of this method should be pointed out. This is a linear model of the system, and as such does not take into consideration control surface rates, SAS authorities, turbulence, or pitch coupling. However, good results have been obtained with this method, as long as gains and motions are limited to reasonable bounds.

The dynamic characteristics for any given mode of oscillation can be represented by the two parameters $\zeta\omega_n$ and ω_d. From these, ζ and ω_n may be calculated:

$$\omega_n = (\zeta\omega_n)^2 + (\omega_d)^2$$

$$\zeta = \frac{\zeta\omega_n}{\omega_n}$$

The equation for ω_n is in the form of a circle from which these parameters may be displayed. It can be seen from figure 94 that once the root locus point is plotted, a circle can be drawn through it, the radius of which is ω_n, the undamped natural frequency. Given ω_n, increasing ζ (from zero) will result in the movement of the root locus point from the ω_d axis (point 1), along the perimeter of the circle, until it reaches the $\zeta\omega_n$ axis (point 2). Point 2 corresponds to critical damping ($\zeta = 1$) where the oscillation becomes aperiodic ($\omega_d = 0$).

The damping ratio ζ is equal to cosine θ. Thus for $\zeta = 0.707$, θ will equal 45 degrees. For a given ζ, θ remains constant, and varying the natural frequency results in changing the radius of the circle.

The three types of damping may be seen on the root locus plot. Underdamping is seen in the oscillatory points above the $\zeta\omega_n$ axis. As the damping is increased to critical damping ($\zeta = 1$) the root locus point will move to the $\zeta\omega_n$ axis. If damping is increased further, overdamping occurs. This is shown by the root locus points splitting and moving along the axis. The time constant of the overdamped mode can be calculated as

$$\tau = \frac{1}{\zeta\omega_n}$$

The many types of motion which can be portrayed and identified on a root locus plot are shown in figure 95.

Root locus plots may be generated for different types of feedback. Three types have been chosen for this report. The first is called open

loop and consists of the basic vehicle with no pilot and no SAS inputs. For this case the stability derivatives C_{ℓ_β} and C_{n_β} and the damping derivatives C_{ℓ_p}, C_{ℓ_r}, C_{n_p}, C_{n_r} control the mode of oscillation. The control surfaces, with no inputs, remain fixed. These points are represented by open symbols in this report. The second case is called closed loop and adds the SAS feedback to the aircraft. In this case the control derivatives $C_{\ell_{\delta a}}$, $C_{\ell_{\delta r}}$, $C_{n_{\delta a}}$, $C_{n_{\delta r}}$, will have an effect on how the vehicle responds proportional to the feedback gain. The closed loop points are represented by closed symbols (or half-closed symbols for only one SAS axis on). Dashed lines represent the connection (intermediate SAS gains) between the SAS-off point and the SAS-on point. This type of plot is shown in figures 20, 36, 37, and 39. The third type of feedback gain incorporates a pilot model into the vehicle. Based on flight results, a model was chosen such that

$$\delta a_{pilot} = k_{pilot} \cdot P$$

For this flight control system, pilot aileron inputs resulted in rudder inputs through the KRA as well as aileron motion. A typical value for k_{pilot} might be 0.3 to 0.5 deg/deg/sec although values as high as 1.5 deg/deg/sec have been noted. Solid lines are used to represent this type of closure with a tick mark to indicate a k_{pilot} of 0.5 deg/deg/sec. Figures 19, 23, 25, 28, 29, 40, 41, 43, 44, 45, and 48 are closures of this third type.

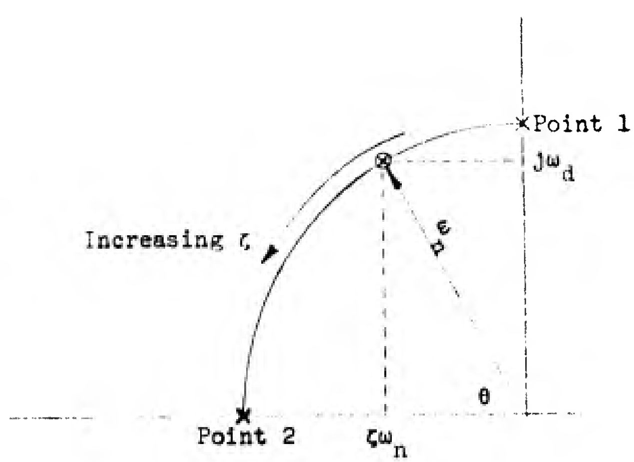


Figure 94. Root Locus Presentation

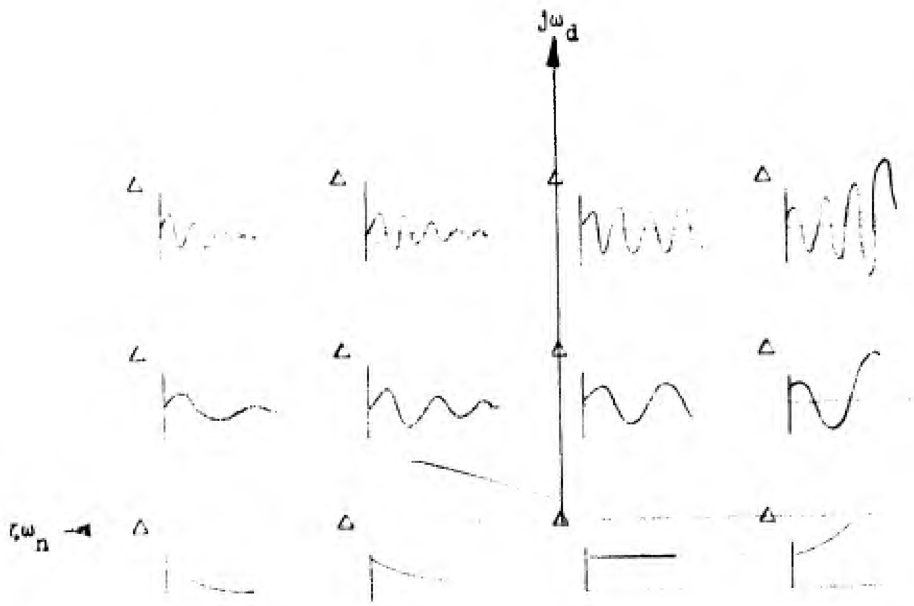


Figure 95. Types of Motion Portrayed on a Root Locus Presentation.

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N/A	Deputy Commander for Operations Air Force Flight Test Center Edwards AFB, California

13. ABSTRACT The handling qualities of the X-24A were determined through a combination of qualitative pilot comments, numerical pilot ratings, and direct and indirect analyses of recorded flight test data. A fixed base six-degree-of-freedom simulator was used extensively to evaluate predicted handling characteristics and to establish trends which were confirmed in flight. The handling characteristics of the X-24A during an approach and landing in still air were excellent. The lateral control capability was inadequate in crosswinds above 10 knots, and the vehicle had a high susceptibility to lateral upsets in light turbulence which was initially disturbing to the pilot. The transonic handling qualities were adequate for a research mission, but precise control was extremely difficult due to an inherent lateral pilot-induced-oscillation tendency and continual small disturbances in the longitudinal and lateral axes. At supersonic speeds the handling qualities were excellent. The rocket engine exhaust plume influenced the handling qualities by producing a longitudinal trim change at transonic conditions and a reduction in directional stability at supersonic conditions. A limited amount of quantitative handling qualities data from X-24A tests were compared with criteria from a proposed specification for lifting reentry vehicles. In most cases the X-24A met the proposed specification. Several of the test maneuvers in the specification were impractical for a vehicle of this type. Some handling qualities deficiencies which were uncovered during the test program were not identifiable by application of the proposed specification.

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	ROLE	WT	ROLE	WT	ROLE	WT
X-24A lifting body						
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approach						
landing						
lateral control						
longitudinal trim						
transonic flight						
supersonic flight						